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Koda et al.

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[54] **PIEZOELECTRICALLY ACTUATED LEVER SWITCH**

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[21] Appl. No.: **79,600**

[52] **U.S. Cl.** .....**310/8.5,** 200/67 DB, 200/181, 310/8.6, 310/9.4, 310/9.7, 317/144

[51] **Int. Cl.** **H04r 17/00**

[58] **Field of Search**.....200/67 DB; 317/144; 310/8, 310/8.3–8.7

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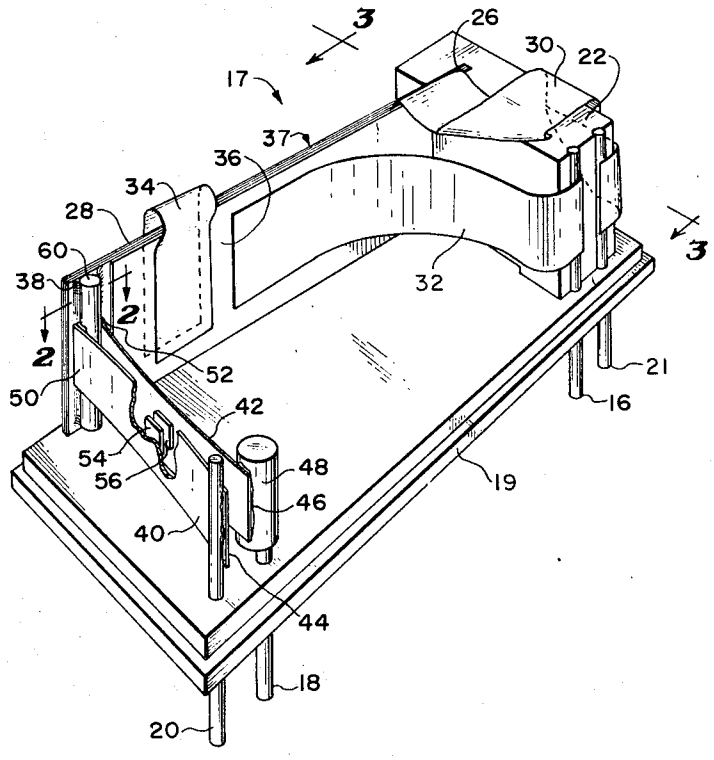
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[57] **ABSTRACT**

A piezoelectric motor is coupled to a pair of electrical contacts by a pair of buckled springs which are called parabolic or arcuate levers. Each parabolic lever carries a contact located at the midpoint of its length. The parabolic levers are positioned adjacent one another and are mounted between the piezoelectric motor and a pair of stationary electrical terminals in such a manner as to be slightly buckled towards each other. When a potential is impressed upon the motor, the buckle in the parabolic levers is increased until the electrical contacts are forced together. The parabolic levers move the contacts much farther than the distance through which the piezoelectric motor moves but press the contacts together with far more force than could be developed by a conventional lever arrangement having the same overall motional advantage.

13 Claims, 15 Drawing Figures



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SHEET 1 OF 4

FIG. 1

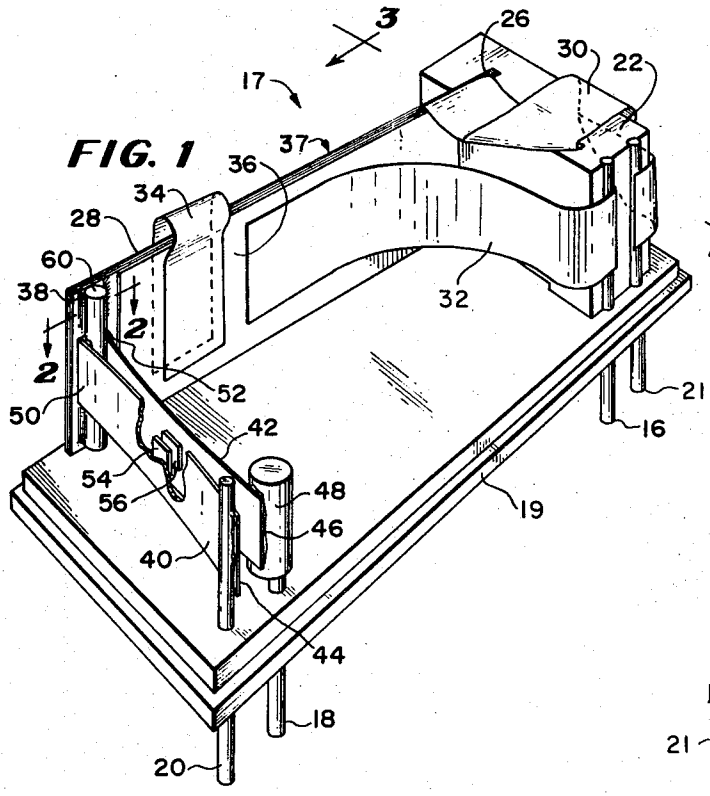
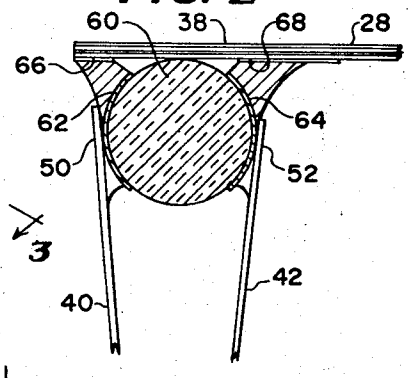


FIG. 2



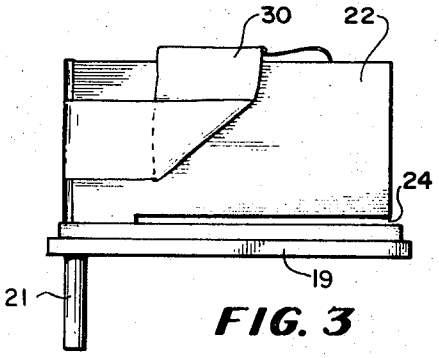


FIG. 3

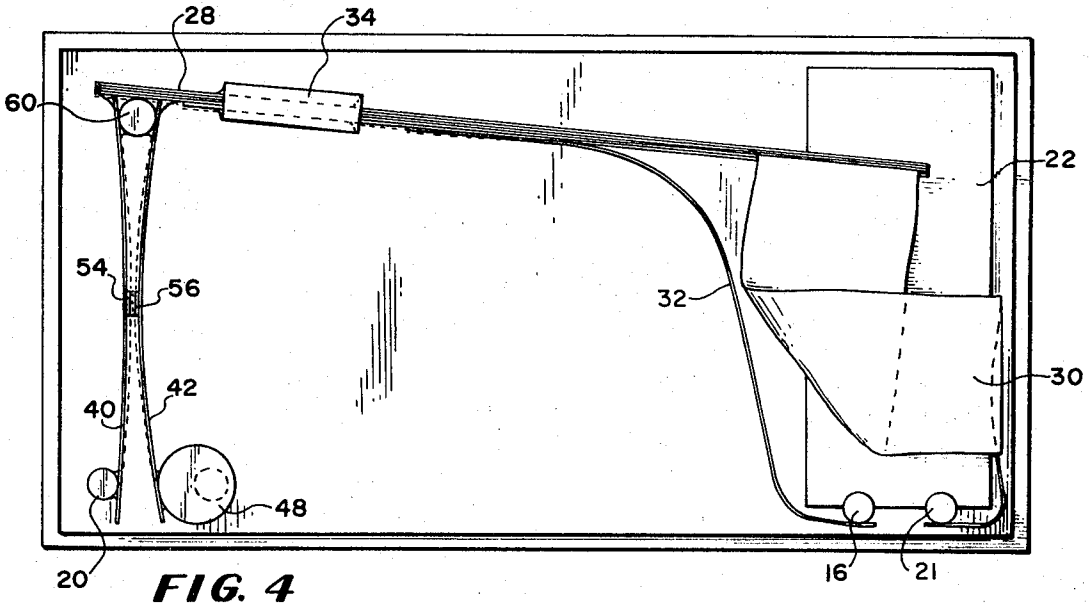


FIG. 4

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FIG. 5

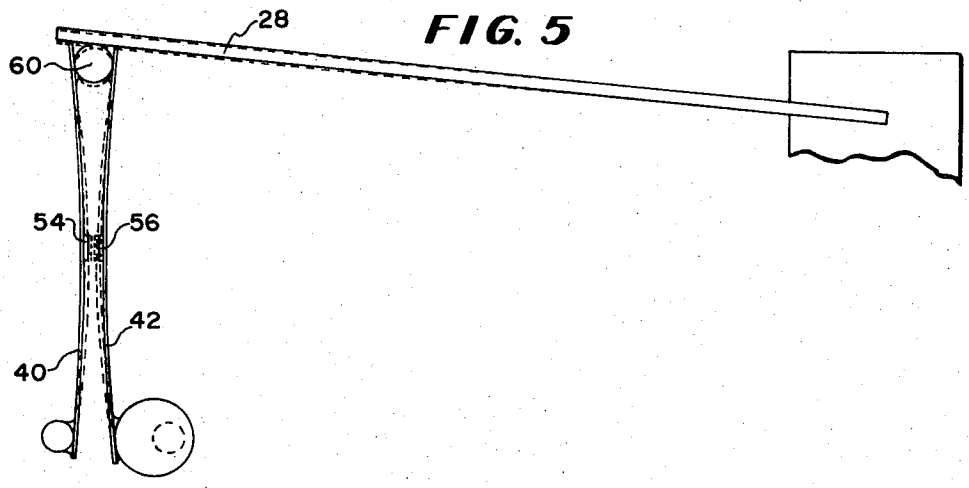


FIG. 6

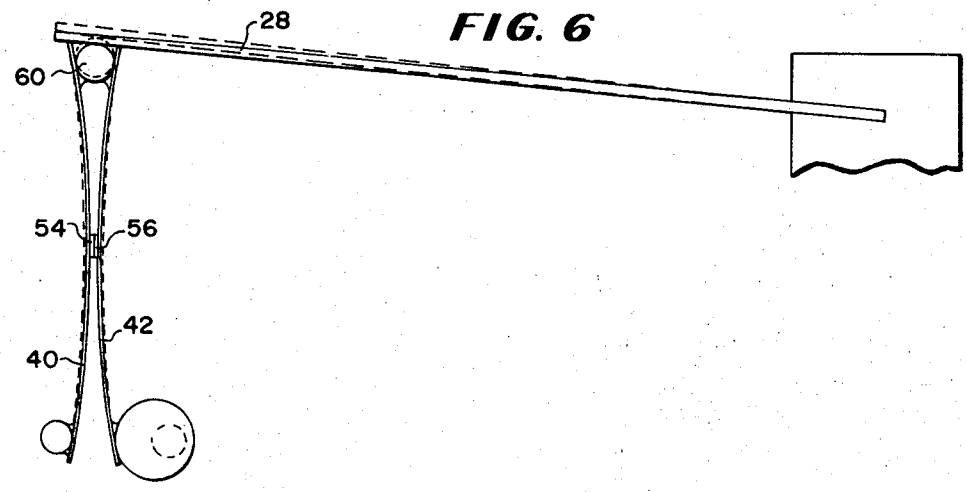


FIG. 7

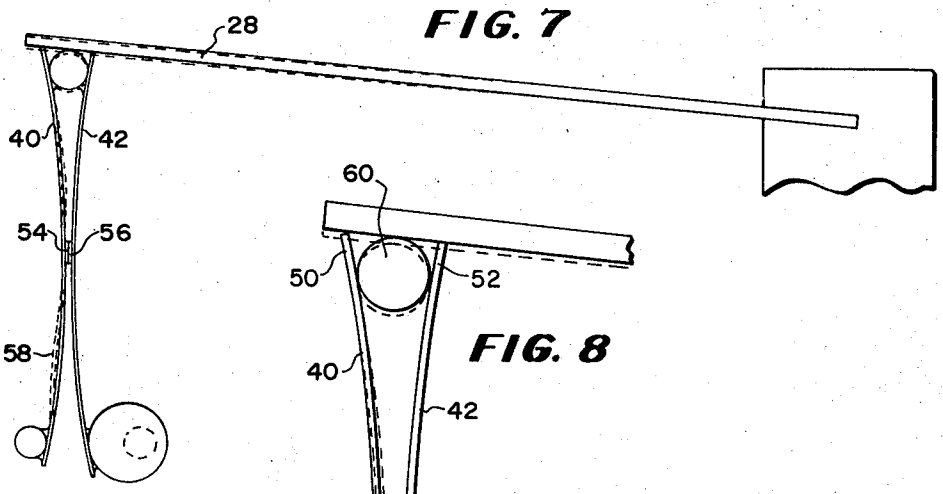


FIG. 8

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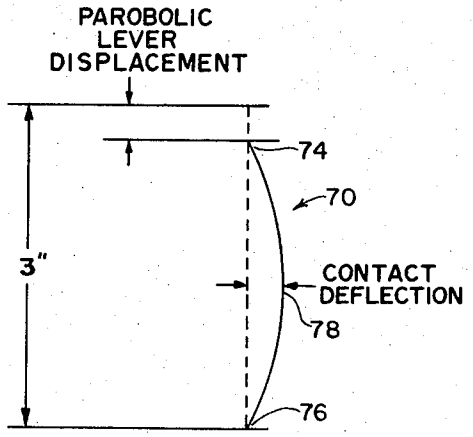


FIG. 9

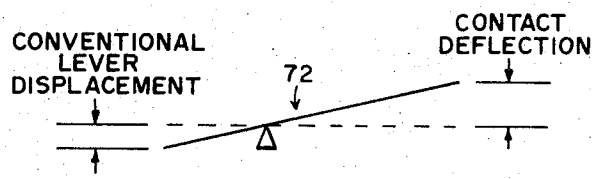


FIG. 10

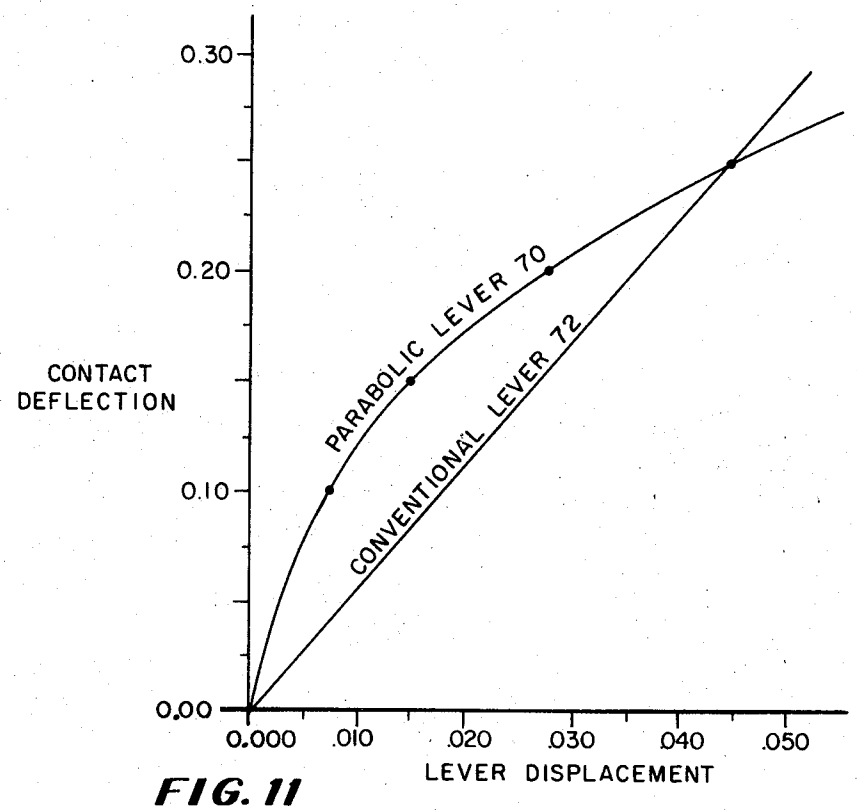


FIG. 11

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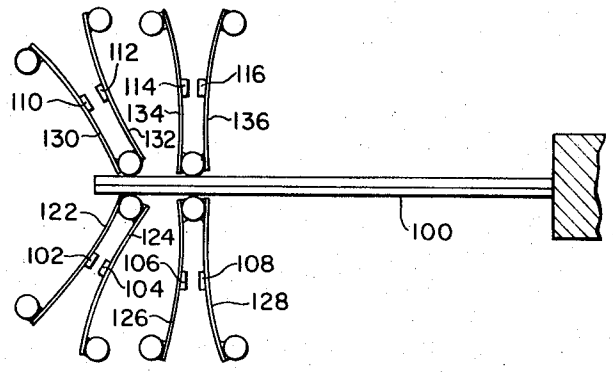


FIG. 12

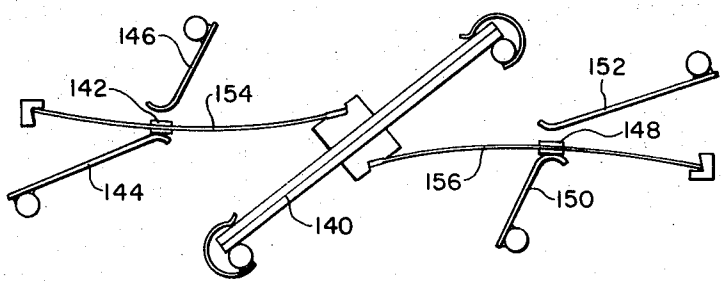


FIG. 13

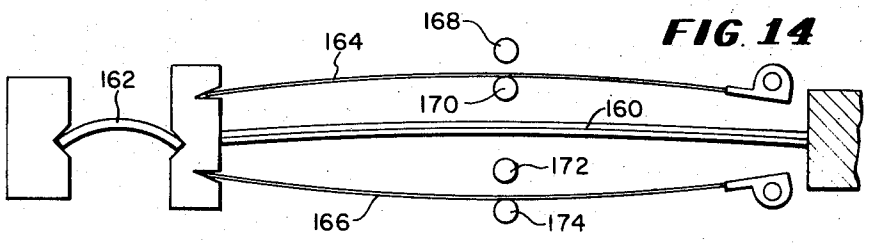


FIG. 14

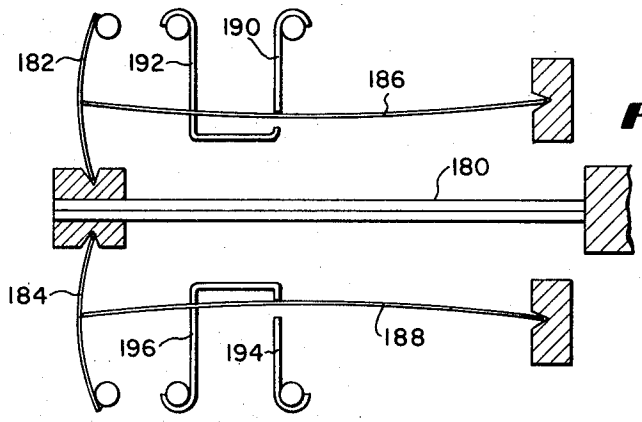


FIG. 15

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PIEZOELECTRICALLY ACTUATED LEVER SWITCH

The present invention relates to relays for closing electrical contacts and, more particularly, to relays wherein the motor or driving element moves through a distance that is small compared to the distance through which the electrical contacts are driven.

During the past twenty years or so, there have been many unsuccessful attempts to design relays in which the electrical contacts are driven together by a piezoelectric motor. Piezoelectric motors can develop a substantial force, but they cannot produce much motion. The electrical contacts in a relay generally must be separated by a substantial distance when open and must press together with a substantial force when closed. Ceramic piezoelectric motors are quite capable of developing the necessary force, but they are not capable of directly moving electrical contacts through a substantial distance.

When lever arrangements are used with piezoelectric motors to develop the necessary contact motion, contact closing force is lost. For example, several different designs of piezoelectrically driven relays incorporating levers have been constructed, and it has been shown that piezoelectric motors which can drive a conventional lever element through the necessary distance can develop a suitable contact closing force only when energized by higher voltages than can be conveniently developed in transistor circuitry. Various workers in the field have attempted to overcome this design problem either by utilizing an exceptionally large piezoelectric motor or else by utilizing a number of motors connected in such a manner as to give either increased motor force or increased motion. While several such arrangements have been proposed, none has proved to be successful due to the problems of temperature compensation, stability, and expense.

A primary object of the present invention is therefore to provide a piezoelectrically driven relay which can be energized directly by low voltage transistor circuitry, which can move a pair of contacts through a satisfactory distance, and which can close a pair of contacts with a satisfactory closing force.

Another object of the present invention is to temperature stabilize such a relay so that it can operate in any environment.

A further object of the present invention is to design such a relay so that the relay contacts wipe against each other as they come into contact thereby keeping themselves clean and thereby insuring a good electrical connection.

Yet another object of the present invention is to design such a relay that may be packaged in a case that is roughly the size of an integrated circuit package and that may be mounted in an integrated circuit type socket.

A more specific object of the present invention is to provide a lever mechanism for such a relay which lends motional advantage to the piezoelectric motor without sacrificing contact closure force.

In accordance with these and other objects, an embodiment of the present invention comprises briefly a piezoelectrically driven relay wherein a pair of electrical contacts are mechanically coupled to a piezoelectric motor by means of a parabolic or arcuate coupling. A parabolic or arcuate lever is a spring that is slightly buckled. The advantage of a parabolic lever is that it can provide both high motional advantage and also high force transmission. A parabolic lever can deliver more force than a conventional lever having the same motional advantage.

In the preferred embodiment, a ceramic piezoelectric motor is fastened to a base at one end by a temperature compensating block. The other end of the motor is arranged to buckle a pair of parabolic levers. The levers extend between the motor and a pair of electrical terminals which are mounted upon the same base as the motor. When a potential is supplied to the motor, the motor buckles the parabolic levers in such a manner that central contact portions of the levers advance towards each other and come into electrical contact with one another. In this manner, the parabolic levers function as contacts for the relay.

When the relay is not energized, the parabolic levers are almost straight, but they are buckled towards each other to some extent by the way in which they are mounted. When the motor first begins to buckle the parabolic levers, the straightness of the parabolic levers gives the motor a great motional advantage in moving the contact portions of the levers, and a very small movement of the motor causes the contact portions of the levers to move over a relatively great distance. By the time the parabolic levers have buckled sufficiently to come into contact with one another, the motional advantage of the parabolic levers is substantially reduced. When the parabolic levers finally come into contact with one another, a force is developed between the contact portions that is much higher than the force which could be developed by a conventional lever having the same overall motional advantage. A relative sidewise motion is also developed within the levers which causes the contact portions to rub slightly together as they come into contact with one another. This rubbing or wiping action cleans the contact areas and insures a good electrical connection.

Further objects and advantages of the present invention are apparent in the detailed description which follows and in the drawings. The points of novelty which characterize the present invention are pointed out with particularity in the claims annexed to and forming a part of this specification.

For a better understanding of the present invention, reference is made to the drawings wherein:

FIG. 1 is a perspective view of an electrostatic relay designed in accordance with the present invention;

FIG. 2 is a fragmentary sectional view taken along the line 2 — 2 in FIG. 1;

FIG. 3 is an elevational view of the relay shown in FIG. 1 taken in the direction of the arrow 3 in FIG. 1;

FIG. 4 is a plan view of the electrostatic relay shown in FIG. 1;

FIG. 5 is a fragmentary plan view similar to FIG. 4 showing the relay as it appears when the contacts are fully opened in solid lines and as it appears when the contacts are halfway closed in broken lines;

FIG. 6 is a fragmentary plan view similar to FIG. 4 showing the relay as it appears when the contacts are fully closed in solid lines and as it appears when the contacts are halfway closed in broken lines;

FIG. 7 is a fragmentary plan view similar to FIG. 4 showing the relay as it appears when the contacts are

fully closed in solid lines and as it appears when the contacts are pressed together with maximum force in broken lines;

FIG. 8 is a fragmentary view of FIG. 7 drawn in such a manner as to exaggerate the wiping which occurs between the relay contacts;

FIG. 9 is a plan view of a parabolic lever illustrating the meaning of lever displacement and of contact deflection with respect to such a lever;

FIG. 10 is an elevational view of a conventional lever illustrating the meaning of lever displacement and of contact deflection with respect to such a lever;

FIG. 11 is a plot of contact deflection as a function of lever displacement for a parabolic lever and for a conventional lever which gives the same overall motional advantage;

FIG. 12 is a multi-contact relay designed in accordance with the present invention;

FIG. 13 is a relay which utilizes individual parabolic levers for each set of contacts rather than pairs of parabolic levers;

FIG. 14 is a relay which includes a toggle action locking spring to hold the relay in one of two stable states; and

FIG. 15 is a relay wherein pairs of parabolic levers are connected in cascade to give still greater contact motion and force.

FIG. 1 shows an electrostatic relay designed in accordance with the present invention and indicated generally by the reference numeral **17**. The relay has four cylindrical electrical terminals **16**, **18**, **20**, and **21** all of which are anchored in a base **19**. A temperature compensating block **22** is molded integrally into the base **19**, and this temperature compensating block **22** joins the base **19** only adjacent the terminals **21** and **16** as is most clearly shown in FIG. 3. For reasons which will be explained below, the temperature compensating block **22** is separated from the vase **19** by an air gap **24** at all other locations.

A piezoelectric motor **28** is mounted in a slot **26** on the block **22** and extends outwardly from the block **22** above the base **19**. The piezoelectric motor **28** is of the type which bends when subjected to an electrostatic field. The motor **28** is positioned in such a manner that it bends through a path which lies in a plane parallel to the base **19**. In the preferred embodiment of the present invention, the piezoelectric motor **28** is a ceramic bender transducer that is constructed by fastening two pieces of piezoelectric ceramic material together in such a manner that they are separated by a conductive layer. A foil conductor **30** extends out from this conductive layer and is electrically connected to the terminal **21**. A similar foil conductor **32** connects the terminal **16** to nickel plating on one side **36** of the motor **28**. Another foil conductor **34** connects the nickel plating on the one side **36** of the motor **28** to nickel plating on the other side **37** of the motor **28** so that oppositely oriented electric fields are developed across the pieces of ceramic material when a potential is applied to the terminals **16** and **21**. In response to such a potential of the proper polarity, the motor **28** bends and a front portion **38** of the motor **28** swings a small distance towards the terminals **18** and **20**.

A pair of parabolic levers or buckled springs **40** and **42** is mounted between the terminals **18** and **20** and the front portion **38** of the motor **28**. The parabolic lever **40** has one end **44** soldered to the terminal **20** and an opposite end **50** fastened to the front portion **38** of the motor **28** in such a manner that the lever **40** buckles slightly towards the temperature compensating block **22** when the relay **17** is not energized. The parabolic lever **42** has one end **46** soldered to an enlarged portion **48** of the terminal **18** and an opposite end **52** fastened to the front portion **38** of the motor **28** in such a manner that the lever **42** buckles away from the temperature compensating block **22** when the relay **17** is not energized. The parabolic levers **40** and **42** thus buckle towards each other. Electrical contacts **54** and **56** are positioned at contact points located midway between the ends of the levers **40** and **42** and are oriented so as to face one another, as is shown in FIGS. **1** and **4**. The shape of the parabolic levers **40** and **42** is not necessarily parabolic. This can be seen especially in FIG. **7** where the lever **40** takes on a serpentine shape.

When an electrical potential of the proper polarity is applied to the terminals **16** and **21**, the motor **28** bends towards the terminals **20** and **18** and buckles the parabolic levers **40** and **42** towards one another. The electrical contacts **54** and **56** are closed by this buckling. An electrical current can now flow between the terminals **18** and **20** over a current path which includes the terminal **18**, the enlarged portion **48**, the parabolic lever **42**, the contact **56**, the contact **54**, the parabolic lever **40**, and the terminal **20** in that order. Once the contacts **54** and **56** have closed, the relay **17** draws no holding current. Removal of the potential from the terminals **16** and **21** does not separate the contacts **54** and **56** because the motor **28** acts as a charged storage capacitor. The charge across the motor **28** maintains the motor **28** in a bent position and thus keeps the contacts **54** and **56** closed. When this charge is ultimately dissipated by flowing over a current path connecting the terminals **16** and **21**, the motor **28** returns to its rest position and the contacts **54** and **56** once again open.

The parabolic levers **40** and **42** are not conventional levers having a well defined fulcrum point and simple input and output motional and force relationships. A parabolic lever gives a decreasing motional advantage and an increasing force advantage as it buckles. A parabolic lever is thus equivalent to a conventional lever wherein the fulcrum point moves towards a position giving an increased output force and a decreased output motion as the lever is actuated. It is this property of the parabolic lever that makes possible the design of a satisfactory electrostatic relay. A parabolic lever allows a piezoelectric motor to move a pair of electrical contacts through a large distance without much deflection on the part of the piezoelectric motor and still to press the contacts together with a substantial force at the end of the stroke.

FIGS. **9**, **10**, and **11** illustrate how a parabolic lever is able to give both increased motional and force advantages to a piezoelectric motor. FIG. **9** shows a parabolic lever **70** that is three inches long. The sever **70** is buckled in a manner similar to the levers **40** and **42** in the relay **17**. Motion of the extreme ends **74** and **76** of the lever **70** towards one another is defined to be the "lever displacement" of the lever **70**. This displacement is measured as indicated in FIG. **9**. Motion of the central portion **78** of the lever **70** away from its rest

position when the lever **70** is straight is defined to be the "contact deflection" of the lever **70** and is also measured as indicated in FIG. **9**. FIG. **11** graphically displays the actual values which are obtained for lever displacement and for contact deflection when the parabolic lever **70** shown in FIG. **9** is buckled. Examination of FIG. **11** shows that when the parabolic lever **70** is only slightly buckled, the contact deflection produced by a given amount of lever displacement is far greater than the contact deflection caused by the same amount of lever displacement when the parabolic lever **70** is more severely buckled.

FIG. **10** shows a conventional lever **72** of the type that has been used in the past to couple a piezoelectric motor to a relay contact. The lever displacement and the contact deflection of the lever **72** are defined in FIG. **10**, and a plot of contact deflection versus lever displacement for this conventional lever **72** is shown in FIG. **11**. The motional advantage of the conventional lever **72** is chosen so that the overall motional advantage of the lever **72** is the same as that of the parabolic lever **70** for a contact deflection of 0.25 inches, as is shown by the intersection of the two curves at this point on the graph.

Let it be assumed that two piezoelectrically driven relays are constructed, one using the parabolic lever **70** to drive a relay contact and the other using the conventional lever **72** to drive a relay contact. Assume further that the motional advantage of the two relays has been adjusted to be the same for a contact motion of 0.25 inches, as explained above. Therefore it takes the same amount of deflection of the piezoelectric motor in either relay to close the contacts. Referring now to FIG. **11**, when the contacts are just short of the point of closing, the parabolic lever **70** gives less contact deflection for a given amount of additional lever displacement than does the conventional lever **72**. Hence, the parabolic lever gives less motional advantage at the contact closure point than does the conventional lever, even though the overall motional advantages of the two arrangements are identical. In mechanics, it is well known that the force advantage of a lever is inversely proportional to the motional advantage of the lever. Since the parabolic lever **70** gives a decreased motional advantage just short of the point of closing, it gives an increased force advantage at this same point of contact. Therefore the parabolic lever **70** requires less relay drive to produce the same contact closing force than does the conventional lever **72**.

If the force advantage of the conventional lever **72** were adjusted so as to equal that of the parabolic lever **70** just short of the point of contact (this is accomplished by shifting the fulcrum point of the conventional lever), the conventional lever **70** would no longer give the same overall motional advantage as the parabolic lever. This loss of motional advantage would mean that a conventional lever with the same force advantage as a parabolic lever would have to be driven through a greater distance by the piezoelectric motor than would the parabolic lever. Since additional displacement of the piezoelectric motor requires additional drive, the parabolic lever **70** would still require less relay drive than would the conventional lever **72**.

Using the graph of FIG. **11** as a guide, it is possible to come up with specific numerical values for the motional and force advantages of the levers shown in FIGS. **9** and **10**. For the conventional lever **72** shown in FIG. **10**, the problem is a simple one. The graph shows that a lever displacement of 0.045 inches produces a contact deflection of 0.25 inches. Defining motional advantage to be the ratio of contact deflection to lever displacement, the motional advantage of the conventional lever **72** is 5.55 and is constant, independent of lever deflection. The number 5.55 signifies that in a relay equipped with the lever **72** for every unit distance travelled by the relay motor, the relay contacts travel 5.55 times farther. In accordance with the theory of conventional mechanics, the force advantage of the lever **72** is the reciprocal of the motional advantage, or 0.18. This means for every unit of force exerted on the lever by the relay motor, the contacts receive a force 0.18 times as great.

Now consider the parabolic lever **70** shown in FIG. **9**. The overall motional advantage given by the lever **70** is the same as that for the conventional lever **72** shown in FIG. **10**, or 5.55. The force advantage given by the parabolic lever **70** is not the reciprocal of the overall motional advantage, but is rather determined by the incremental motional advantage of the parabolic lever **70** when the lever is deflected to the point where relay contacts driven by the lever would touch one another. This incremental motional advantage is equal to the slope of the parabolic lever curve shown in FIG. **11** at the point on the curve corresponding to a contact deflection of 0.25 inches. Examination of the graph in FIG. **11** reveals that the force advantage given by the parabolic lever **70** is 0.34. This is almost double the force advantage given by a conventional lever **72**. Hence, the parabolic lever **70** shown in FIG. **9** is able to provide almost twice the contact force that can be obtained from the conventional lever **72** when the two levers have the same overall motional advantage.

The above discussion has been simplified somewhat by the assumption that the parabolic lever **70** begins with no deflection whatsoever and also by the assumption that the parabolic lever **70** is free to buckle all the way along its length and is not inhibited by rigid mountings at **74** and **76** or by a stiff contact mounted at **78**. Even if these factors are taken into account, however, the parabolic lever still generates greater contact force for less piezoelectric motor travel than a conventional lever. An additional factor that must be considered in the design of an actual parabolic lever is the fact that once the contacts come together, the shape of the parabolic lever is changed considerably by the contact force. This change in shape makes necessary a small additional deflection of the piezoelectric motor before maximum contact force is developed. Even when this factor is taken into account, the parabolic lever is still substantially more efficient in its operation than a conventional lever.

The above mentioned properties of parabolic levers are further illustrated in FIGS. **5** through **7**. In FIG. **5**, the piezoelectric motor **28** is in its rest state and the contacts **54** and **56** are fully separated. In broken lines, the position of the piezoelectric motor **28** is shown when the contacts **54** and **56** have moved halfway towards engagement. The distance through which the motor **28** has moved in order to produce this amount of contact motion is quite small when compared to the

distance through which the contacts **54** and **56** have moved. The large motional advantage given by the parabolic levers during the first half of the relay closure motion is thus clearly apparent in FIG. **5**.

In FIG. **6**, the position of the various relay components when the contacts **54** and **56** first touch one another is shown. In broken lines, the position of the relay components when the contacts **54** and **56** are halfway open is shown. FIG. **6** shows clearly that far more motion on the part of the motor **28** is required to drive the contacts **54** and **56** over the last half of their path of travel than was required (as shown in FIG. **5**) to drive the contacts **54** and **56** over the first half of their path of travel. The decrease in motional advantage with parabolic lever deflection is thus apparent in FIG. **6**. The theory of mechanics then predicts that the force advantage at the point of contact is increased over what it would have been had the motional advantage not decreased. Maximum motional advantage is thus achieved when the contacts are widely separated, and maximum force advantage is achieved when the contacts are close together. Hence, the parabolic levers **40** and **42** function as a pair of levers whose fulcrum point shifts as the levers are deflected so as to maximize the relay contact closing force while minimizing motion of the piezoelectric motor **28**.

FIG. **7** illustrates the change in shape which occurs in the parabolic levers **40** and **42** when a force is developed between the contacts **54** and **56**. The solid line portion of FIG. **7** is identical to the solid line portion of FIG. **6**. The broken line portion of FIG. **7** illustrates the position of the various relay components when the motor **28** is causing maximum force to be applied between the contacts **54** and **56**. It can be seen that the parabolic levers **40** and **42** change their shape considerably as maximum force is developed. This change in shape is caused by the development of shear forces within the parabolic levers **40** and **42** and by the reduction in the magnitude of bending moments present within the levers **40** and **42**. Instead of having a roughly parabolic or sinusoidal shape, the parabolic levers now assume a shape that is much flatter adjacent the contacts **54** and **56** and much more curved at the end portions of the levers. It is even possible for a slight reverse buckle to develop in one of the levers, as is shown at **58** in FIG. **7**. Only a slight additional deflection of the motor **28** is required to take up the slack caused by this change in lever shape, and hence the loss in relay efficiency which results from this change is small and relatively insignificant.

Another feature of the present invention is illustrated in FIG. **8**. When the contacts **54** and **56** come together, they are rubbed together slightly due to unequal sidewise motion of the parabolic levers **40** and **42**. This rubbing action is shown in an exaggerated manner in FIG. **8**. In part, this rubbing is due to the nonuniform buckling of the parabolic levers **40** and **42** when the contacts **54** and **56** come together. In part, it is due to the fact that the parabolic lever **40** is deflected farther than the parabolic lever **42**. The lever **40** is deflected farther because the lever **40** is attached to the piezoelectric motor **28** at a point that is farther away from the center of bending of the piezoelectric motor **28** than the point at which the lever **42** is attached. In other words, when the motor **28** bends, it deflects the end **50** of the parabolic lever **40** farther than it deflects the end **52** of the parabolic lever **42**. This uneven deflection causes the contact **54** to shift farther in a sidewise direction than does the contact **56** and thereby results in a wiping action. In FIG. **8**, the wiping action is primarily caused by nonuniform buckling of the parabolic lever **40** at the point **58** (FIG. **7**), and hence the contact **54** is slightly above the contact **56**. The contacts **54** and **56** wipe against each other in this manner each time the relay **17** is actuated. This wiping action keeps the contacts **54** and **56** clean and also insures a good electrical connection every time the relay **17** is actuated.

The temperature compensating block **22** is shown in FIGS. **1**, **3**, and **4**. In the preferred embodiment, this block **22** is constructed of the same type of plastic from which the base **19** is constructed and is molded integrally into the base **19**. Alternatively, the block **22** may be constructed of a metal, such as bronze or zinc, or of any other suitable material. In any case, the block **22** is chosen to have a coefficient of expansion and contraction with changes in temperature that compensate for the expansion and contraction of the parabolic levers **40** and **42**. In FIG. **3**, it can be seen that the temperature compensating block **22** is attached to the base **19** only adjacent the contacts **16** and **21**. The block **22** is separated from the base **19** by an air gap **24** over the remainder of its length. When the block **22** expands or contracts with changes in temperature, the block **22** shifts the piezoelectric motor **28** away from or toward the electrical terminals **16**, **18**, **20**, and **21**. If the proper coefficient of expansion is chosen for the block **22**, the block **22** can exactly compensate for any changes which occur in the length of the parabolic levers **40** and **42** with changes in temperature. While a perfect temperature compensation can be achieved, it has been found more desirable in practice to overcompensate. This is desirable because the actuation potential of the relay **17** can then be held relatively constant. By overcompensating, the spacing between the contacts **54** and **56** can be forced to increase with increasing temperature, thereby overcoming the increased efficiency of the piezoelectric motor **28** with increasing temperature. In one embodiment, zinc is used in constructing the temperature compensating block **22**. This zinc block overcompensates, and thus results in increased contact spacing with increasing temperature. The spacing between the contacts **54** and **56** is adjusted to 10 mils at −65° C. At room temperature, the contact spacing increases to 11 or 12 mils, and at +125° C., the contact spacing increases to 15 mils. In this embodiment, the relay **17** actuation potential is held to any value within 10 percent of 24.5 volts from −20° to +70° C., and the relay **17** is operable over the entire temperature range from −65° to +125° C. In another embodiment, a brass temperature compensating block **22** is used to compensate almost perfectly for changes in the length of the parabolic levers **40** and **42** and to maintain a constant 10 mil contact spacing. The relay actuating voltage for this embodiment is lower than for the embodiment utilizing a zinc temperature compensating block, but the actuating voltage shifts with changes in temperature. This actuating voltage shift in the temperature can be a useful property, since this temperature sensitivity converts the relay **17** into a

thermostat. If the contact spacing does not have to be held at 10 mils and if variations in actuation potential are not detrimental, then any convenient material may be used for the temperature compensation block. If terminals are provided at the proper locations for attaching the piezoelectric motor, the block may be omitted entirely. As mentioned above, in the preferred embodiment the block **22** is molded from the same plastic of which the base **19** is constructed and this plastic is chosen to have the desired coefficient of expansion with changes in temperature.

As shown in FIG. **1**, the contacts **54** and **56** are mounted on the parabolic levers **40** and **42**. The parabolic levers **40** and **42** are constructed from beryllium copper alloy (No. 10) heat treated for service as a spring. The contacts **54** and **56** are formed out of a silver magnesium nickel alloy (No. 15065, Engelhard Industries Division, Newark, New Jersey) and are gold plated to a thickness of 0.001 inches. The contacts **54** and **56** are attached to the levers **40** and **42** by a diffusion process during which the contacts and the levers are heated between steel electrodes at 930° F. for 7 seconds. This binds the contacts **54** and **56** to the levers **40** and **42** without relieving the levers **40** and **42** of their temper.

FIG. **2** shows the way in which the parabolic levers **40** and **42** are attached to the front portion **38** of the motor **28**. A glass cylinder **60** is axially coated along two of its sides with cadmium coatings **62** and **64** as shown. The cadmium coatings **62** and **64** do not join at any point and are electrically insulated from one another by uncoated sections of the glass cylinder **60**. Nickel coatings **66** and **68** are placed upon the piezoelectric motor **28** at two locations respectively adjacent the ends **50** and **52** of the parabolic levers **40** and **42**. Uncoated sections of the motor **28** separate the nickel coatings **66** and **68** from each other and from other coated portions **36** and **37** of the motor **28**. The cylinder **60** is carefully soldered to the motor **28** in such a manner that the coating **62** is soldered to the coating **66** and the coating **64** is soldered to coating **68**. The parabolic levers **40** and **42** are then brought into position and are buckled as desired. The end portions **50** and **52** of the levers **40** and **42** are then respectively soldered to the coatings **62** and **64** as shown in FIG. **2**. In this manner, the parabolic levers **40** and **42** are securely attached to the motor **28** but are not connected together by any electrically conducting path. If desired, a suitable cement such as an epoxy resin can be used in place of the solder, and then the metallic coatings can be dispensed with or replaced by a suitable epoxy binding coating.

The opposite ends **44** and **46** of the parabolic levers **40** and **42** are soldered directly to the terminals **20** and **18**, as shown in FIG. **1**. The soldering is carried out in such a manner that the levers **40** and **42** are not relieved of their temper.

The size of the relay shown in FIG. **1** is 0.875 inches long by 0.450 inches wide by 0.350 inches high. The terminal centers are spaced so as to be "dual in-line" compatible. The enlarged portion **48** of the terminal **18** allows the ends **44** and **46** of the parabolic levers **40** and **42** to be closer together than the terminals **18** and **20**. The relay **17** can be mounted in a **16** pin integrated circuit socket of the conventional type. The contact resistance is 0.1 ohms maximum, and the contact capacitance is approximately 0.3 picofarads. Input-to-output terminals isolation is 10^{11} ohms. For a typical unit, the nominal operate voltage is 24 volts, with pickup or actuation at 20 volts and dropout or deactuation at 18 volts. This close differential between pickup and dropout is characteristic of the relay. Much lower operate voltages are obtainable with different contact spacing geometries and force requirements so that direct drive of the relay **17** by integrated circuits is definitely possible. The power input requirements of the relay **17** are extremely low. The circuit equivalent of a typical relay **17** motor is a resistor having a resistance of 5×10^9 ohms connected in parallel with a capacitor having a capacitance of 0.05 microfarads. If rapid deactuation or release is desired, it is necessary to connect a resistor having a resistance of 10^3 to 10^5 ohms across terminals **16** and **21** of the relay **17**.

The operate time of relay **17** is less than 0.5 milliseconds, and the release time is less than 0.25 milliseconds when the terminals **16** and **21** are shunted with a resistor having a resistance of 10^4 ohms. The maximum drive frequency for the relay **17** is in excess of 1,000 Hz. The relay **17** can be made resonant, and when driven at resonance the relay **17** picks up at one-fourth to one-tenth the nominal actuation potential. The center frequency of this resonance may be adjusted by varying the characteristics of the relay **17**.

FIGS. **12** through **15** illustrate other embodiments of the present invention. In FIG. **12**, a single piezoelectric motor **100** is coupled to four pairs of contacts **102–104**, **106–108**, **110–112**, and **114–116** by four pairs of parabolic levers **122–124**, **126–128**, **130–132**, and **134–136**. This structure can be wired so as to function as a double pole, double throw switch and can be arranged to have a center-off position with all contacts open. FIG. **13** illustrates a configuration wherein a single piezoelectric motor **140** drives a first contact **142** between poles **144** and **146** and drives a second contact **148** between poles **150** and **152**. The contact **142** is mounted upon a first parabolic lever **154**, and the contact **148** is mounted upon a second parabolic lever **156**. FIG. **14** illustrates a bistable arrangement wherein a piezoelectric motor **160** is held in one of two stable positions by a toggle action spring **162**. The motor **160** buckles a pair of parabolic levers **164** and **166** respectively between terminal pairs **168–170** and **172–174**. This arrangement also can act as a double pole, double throw toggle switch. FIG. **15** illustrates a first pair of parabolic levers **182** and **184** driving a second pair of parabolic levers **186** and **188** so as to multiply the motional and force advantage given by a single parabolic lever. A piezoelectric motor **180** buckles a first pair of parabolic levers **182** and **184**, and these in turn buckle the second pair of parabolic levers **186** and **188** so as to drive the levers **186** and **188** respectively between the contact pairs **190–192** and **194–196**. Many other similar arrangements are also possible whereby different combinations of make or break can be produced using parabolic levers and piezoelectric motors. It should be noted that while the above illustrated embodiments all employ a piezoelectric bending type motor other forms of piezoelectric motors generating shear, axial displacement, and longitudinal motion can also be employed to drive contacts with the aid of parabolic levers.

One additional modified version of the relay **17** shown in FIG. **1** deserves mention. If the contacts **54** and **56** in FIG. **1** are magnetic, or if magnetic material is placed on the opposite sides of the levers **40** and **42** from the contacts **54** and **56**, the closing force of the contacts **54** and **56** is increased, and the relay may even be made self-locking. Such a magnetic contact arrangement is advantageous because it increases the contact closing force without requiring increased drive from the piezoelectric motor **28**. Since the motor **28** gives the greatest force advantage when the contacts **54** and **56** are closed, and since the magnetic coupling between the contacts is also maximum when the contacts are closed, the strength of the magnetic pull is preferably adjusted so that the magnets may be pulled apart by the action of the motor **28**. As the contacts separate, the force advantage of the motor **28** decreases, but the force between the magnetic elements also decreases. The motor **28** therefore is able to fully separate the contacts and overcome the magnetic attractive force.

While there have been shown the preferred embodiments of the present invention, it will be understood that numerous modifications and changes will occur to those skilled in the art. The appended claims are therefore intended to encompass all such modifications and changes as come within the true spirit and scope of the present invention.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A relay comprising:
a base;
a pair of terminals supported by said base;
a piezoelectric bender transducer having first and second end portions, the first end portion positioned adjacent said pair of terminals;
a pair of arcuate levers each mounted between one of said terminals and the first end portion of said transducer and buckled towards one another, said levers mounted at approximate right angles to said transducer; and
a temperature compensating block rigidly connecting the second end portion of said transducer to said base and extending from a point of attachment with said transducer to a point of attachment with said base in a direction roughly parallel to the long axes of the arcuate levers.

2. A relay in accordance with claim **1** wherein each arcuate lever carries an electrical contact positioned midway along the length of the lever and wherein the contacts are further positioned to face one another.

3. A relay in accordance with claim **1** wherein the base and the temperature compensating block are integrally formed of the same material.

4. A relay in accordance with claim **1** wherein the coefficient of expansion of the temperature compensating block is chosen to compensate for changes in the length of the arcuate levers, thereby maintaining a relatively constant contact spacing.

5. A relay in accordance with claim **4** wherein the temperature compensating block is constructed from brass.

6. A relay in accordance with claim **1** wherein the coefficient of expansion of the temperature compensating block is chosen to substantially stabilize the potential which must be applied to the transducer to force the contacts together.

7. A relay in accordance with claim **6** wherein the temperature compensating block is constructed from zinc.

8. A contact driving mechanism comprising:
a base;
an arcuate lever having first and second ends;
an electrical contact mounted upon said lever and positioned at or near the center of one side of said lever;
means for mounting the first end of said lever on said base;
a piezoelectric bender transducer having actuation terminals and having first and second ends;
means for attaching the second end of said lever approximately perpendicularly to the first end of said bender transducer to keep said lever buckled with said contact on the convex side of said lever; and
a temperature compensating block rigidly connecting the second end of said bender transducer to said base and extending from a point of attachment with said transducer to a point of attachment with said base in a direction roughly parallel to the long axis of said arcuate lever.

9. A relay comprising:
a motor;
at least one pair of electrical contacts;
a pair of arcuate levers connecting each pair of electrical contacts to said motor and arranged to drive the pairs of contacts together when said motor is energized to buckle the corresponding pairs of arcuate levers;
said motor comprising a piezoelectric bender transducer having one end fixed with respect to one end of each pair of levers and having the other end attached to the other end of each pair of levers, whereby the pairs of contacts are deflected towards one another when a potential of the proper polarity is applied to the piezoelectric bender transducer;
a pair of electrical terminals to which the one end of each pair of arcuate levers is attached, and wherein each lever is electrically connected to one terminal;
a single base structure supporting both the fixed end of the transducer and the pairs of electrical terminals; and
a rod to which the other end of each pair of arcuate levers are attached in such a manner that the levers are permanently buckled slightly towards one another, said rod and the other end of said pair of arcuate levers both being attached to the other end of the piezoelectric bender transducer.

10. A relay comprising:
a base;
a pair of posts mounted on said base;
a piezoelectric bender having first and second ends, said first end rigidly attached to said base;
a pair of contacts;
a pair of arcuate levers to each of which one of said contacts is attached; and
means for mounting each arcuate lever between one of said pair of posts and the second end of said piezoelectric bender and for positioning each lever approximately perpendicular to said bender with said contacts facing one another and with said levers buckled towards one another.

11. A relay in accordance with claim **10**, wherein the means for mounting include a rod attached to said bender and also to each of said levers, said rod separating said levers and maintaining the buckle in said levers.

12. A relay comprising:

a base;

at least one pair of electrical contacts;

an arcuate lever corresponding to each electrical contact, each contact being mounted at approximately the midpoint of the corresponding lever;

a piezoelectric bender transducer having first and second ends, said first end attached to said base, and also having electrical actuation terminals;

temperature compensating means attaching said first end of said bender transducer to one end of said base for expanding and contracting to compensate for changes in the length of the arcuate levers with temperature; and

mounting means for attaching one end of each lever to the second end of said bender transducer, for attaching the other end of each lever to said base, and for positioning said levers in pairs facing one another and buckled towards one another with the contacts carried by each pair of levers facing one another, said levers extending roughly perpendicularly to the major axis of said bender transducer;

whereby said pairs of contacts are forced together with a wiping action when a potential is applied to the actuation terminals of the bender transducer.

13. A relay comprising:

a base;

at least one pair of electrical contacts;

an arcuate lever corresponding to each electrical contact, each contact being mounted at approximately the midpoint of the corresponding lever;

a piezoelectric bender transducer having first and second ends, said first end attached to said base, and also having electrical actuation terminals;

a temperature compensating block attaching the first end of the transducer to the base and extending from a point of attachment with the base to a point of attachment with the transducer in a direction roughly parallel to the length of the associated pair of arcuate levers;

a pair of electrical terminals to which the other end of each pair of arcuate levers is attached, and wherein each lever is electrically connected to one terminal; and

mounting means for attaching one end of each lever to the second end of said bender transducer, for attaching the other end of each lever to said base, and for positioning said levers in pairs facing one another and buckled towards one another with the contacts carried by each pair of levers facing one another, said levers extending roughly perpendicularly to the major axis of said bender transducer;

whereby said pairs of contacts are forced together with a wiping action when a potential is applied to the actuation terminals of the bender transducer.

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