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W. L. CHERRY, JR

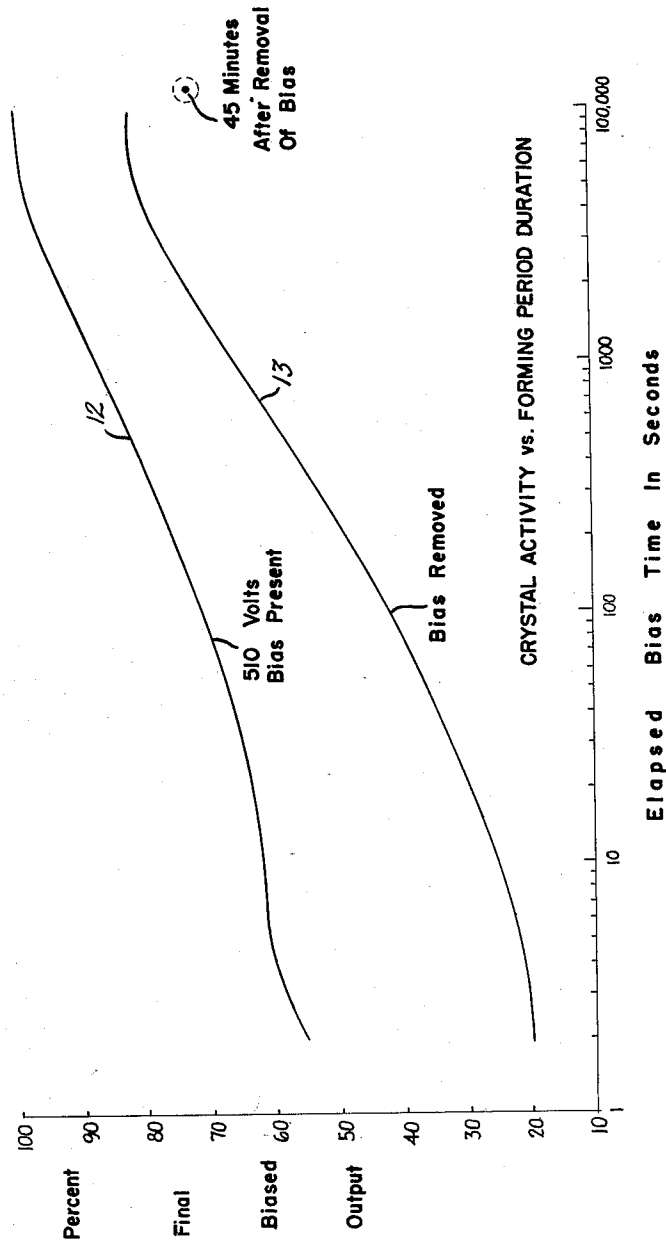
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PROCESS OF PRODUCING PIEZOELECTRIC TRANSDUCERS

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Fig. 3



WALTER L. CHERRY JR.
INVENTOR.

BY *J. Clarke Nagay*
HIS ATTORNEY

Jan. 16, 1951

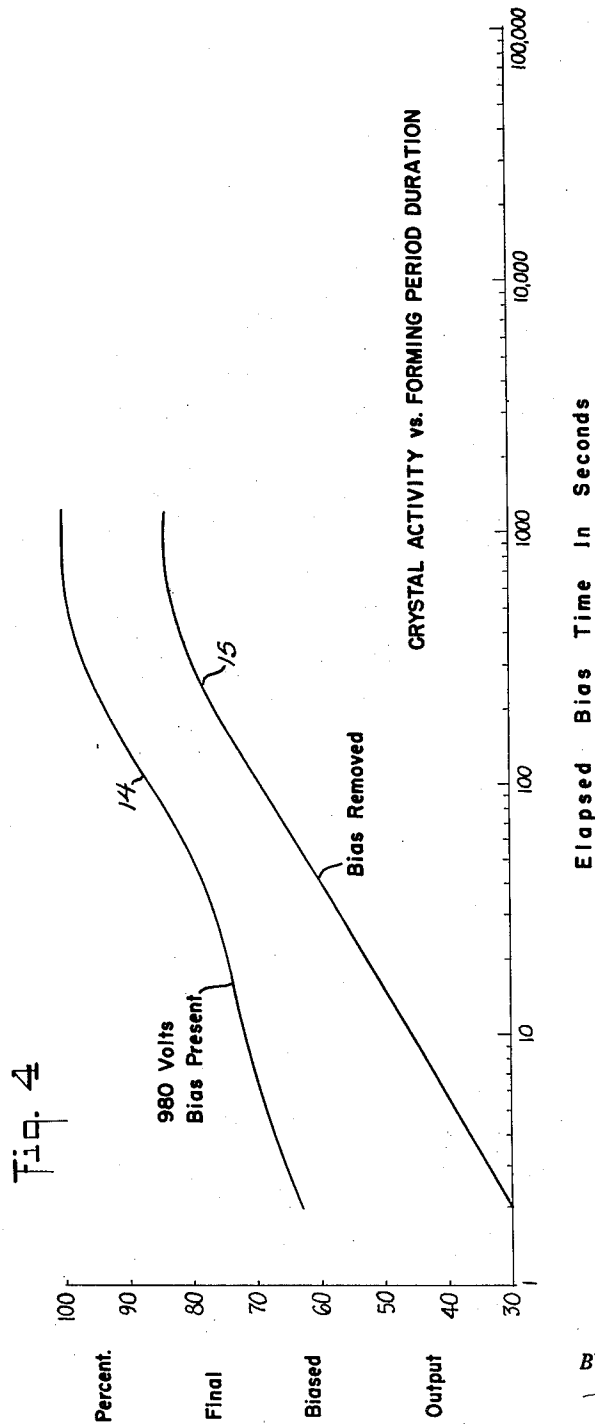
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WALTER L. CHERRY JR.
INVENTOR.

BY *J. Clarke Nagley*
HIS ATTORNEY

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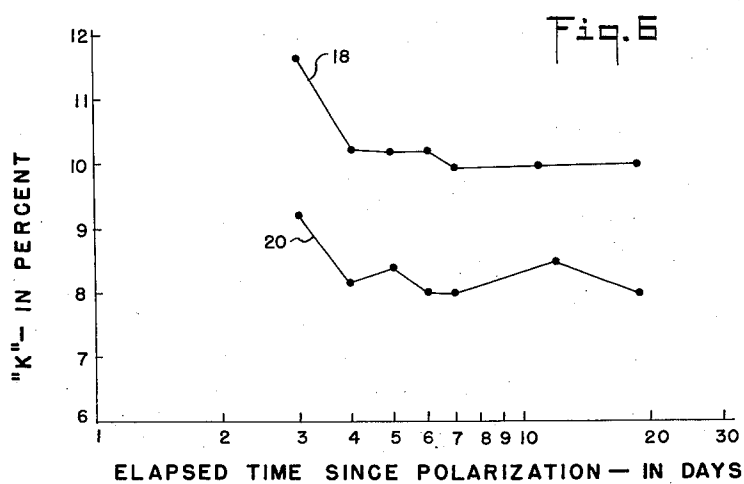
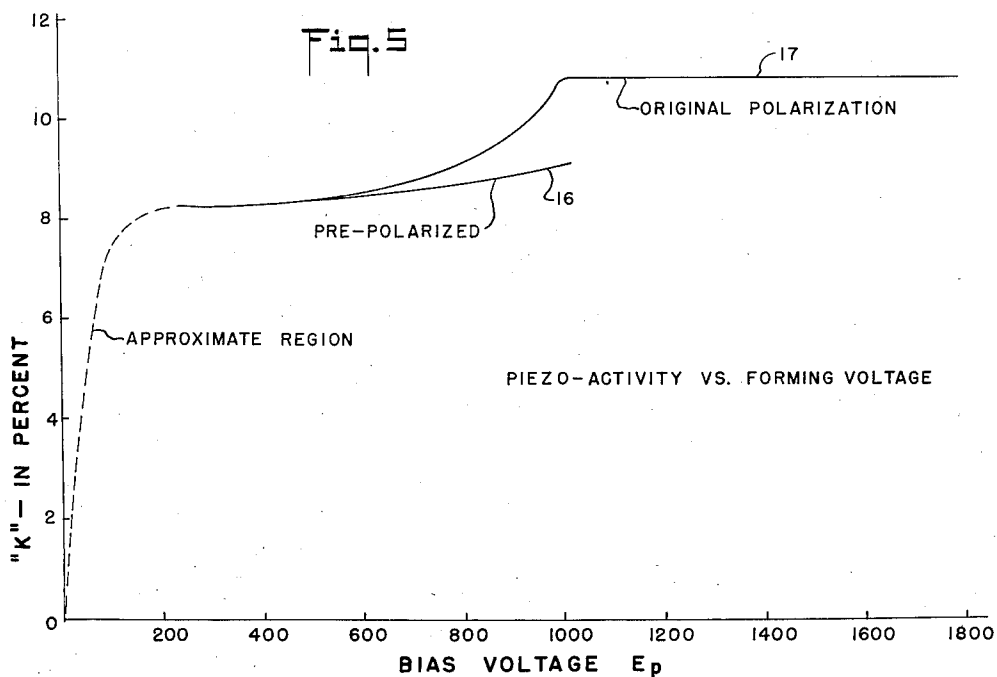
W. L. CHERRY, JR

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PROCESS OF PRODUCING PIEZOELECTRIC TRANSDUCERS

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4 Sheets-Sheet 4



WALTER L. CHERRY JR.
INVENTOR.

BY *Bruce G. Bishop*
HIS AGENT

UNITED STATES PATENT OFFICE

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PROCESS OF PRODUCING PIEZOELECTRIC
TRANSDUCERSWalter L. Cherry, Jr., Northbrook, Ill., assignor to
Zenith Radio Corporation, a corporation of
Illinois

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6 Claims. (Cl. 171—327)

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This invention relates to a process for making piezo-electric transducers and to the piezo-electric transducers formed by that process and has for an object to provide such a process which is relatively simple and easy to carry out and to provide a resulting product which is inexpensive and rugged and, although highly sensitive, is substantially unaffected by ordinarily encountered temperature and humidity conditions.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The present invention itself, both as to its organization and manner of operation, together with further objects and advantages thereof may best be understood by reference to the following description taken in connection with accompanying drawings in which:

Figure 1 illustrates one embodiment of the product of my invention, and

Figures 2 through 6 illustrate certain characteristics of the product observed during and after the process of making the product.

In Figure 1, a body 1, which is a solid polycrystalline aggregate, is provided on opposite faces with electrodes 2 and 3 to which suitable conductors 4 and 5 are connected. Application of pressure to the body in any direction which induces a change in the dimension of the body lying between the electrodes causes the formation of an electric charge on the two electrodes, so that the charge influences an externally connected circuit through the conductors 4 and 5. Such force may be applied to the body by a phonograph needle which runs in the groove of a phonograph record, so that alternating voltages developed between the conductors 4 and 5 accurately represent sound which was originally used to form undulations in the groove on such record.

The solid polycrystalline aggregate which forms the body 1 is formed of individual crystals bonded together, the crystalline material of which has a transition temperature above which, it is believed by reason of symmetry, the individual crystals are not piezo-electric but below which transition temperature such crystals are piezo-electric. These individual crystals in the solid polycrystalline aggregate are formed and then caused to become piezo-electric in the aggregate by the following process which is believed at present to cause the piezo-electric axes of individual crystals to assume a preferred common direction.

One such specific polycrystalline aggregate body which was found to be highly piezo-electric and permanent in nature is formed as follows:

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Barium titanate, thoroughly mixed with small amount of a glass forming oxide, such, for example, as silica with possible additions of alumina, magnesia, or calcium oxide, is brought to a sufficiently high temperature to bond the aggregate into a solid body which may be of any desired form.

While glass-forming oxides have been mentioned as such a bonding agent, and are preferred because their use as the bonding agent renders the resulting body substantially impervious to normally encountered temperatures and humidity conditions, any bonding agent may be utilized which has high electrical resistance under the desired working conditions and which is sufficiently rigid to maintain individual crystals of barium titanate substantially immobile. At the same time the bonding agent should occupy a sufficiently small space that the piezo-electric effect is not reduced by the presence of inert materials. An example of another suitable bonding agent for certain purposes is phenolformaldehyde and other similar resins.

Another example of a suitable polycrystalline aggregate body is as follows: Barium strontium titanate mixed thoroughly with a suitable bonding agent as previously described, is brought to a sufficiently high temperature to bond the aggregate into a solid body of desired form.

Electrodes are formed on two opposite faces of the body. These electrodes may be of any suitable conducting material such as metal foil or paint. Good results have been secured with electrodes of silver paint baked on at a suitably elevated temperature. Conductors 4 and 5 are attached to the electrodes securely, as by baking these on at the conduction point or soldering them thereto.

With the device thus constructed a unidirectional potential having a magnitude preferably sufficient to produce a field of at least 2500 volts per centimeter in the body is applied between the two electrodes 2 and 3 through conductors 4 and 5 for a time sufficient to attain a substantial amount of permanent piezo-electric effect in the body. Good results have been obtained both at normal room or ambient temperatures and at elevated temperatures which, however, must be lower than the above mentioned transition temperature. Because of the convenience, it is now preferred to produce this permanent piezo-electric effect at normally encountered room temperatures.

Experience indicates that the continuous potential applied should be preferably as large as possible, provided, however, that it is not so

large as to cause the body to become so substantially semi-conducting as to decrease or destroy its usefulness. Such action appears to occur by actual dielectric breakdown or sparking. For the barium titanate aggregates, it has been found that a voltage is suitable which produces a field as high as 25,000 volts per centimeter in the body.

In Figure 2, the following characteristics are shown graphically for such a body whose thickness is about 0.4 millimeter and whose material is a bonded aggregate of barium titanate. The percentage of final output is plotted as ordinate and the time for which a forming voltage of 340 volts was applied is plotted as abscissa on a semi-logarithmic scale. The upper curve 10 indicates such output measured in the presence of the forming voltage, while the lower curve 11 indicates such output voltage measured one minute after removal of the forming voltage.

In these data all actual readings of "output" were taken by finding the audio output voltage with a mechanical force of known magnitude applied at an audio frequency rate, from which the mechano-electrical coupling factor "K" is readily determined. This coupling factor "K" is equal to the square root of the inverse ratio of mechanical energy per cycle of applied vibration to electrical energy per cycle of alternating current energy thus produced.

It is evident from both curves 10 and 11 that the voltage output of the bodies for a given applied stress increased over a substantial period of time until a rather well defined saturation was produced which occurred only after a voltage was applied continuously for from about 5000 to 20,000 seconds, or from about one and one half to eight hours.

Figure 3 shows similarly plotted curves 12 and 13 when 510 volts was applied continuously to similar bodies. These curves show that similar saturation occurred in somewhat less time (about 7000 seconds, or about 2 hours).

Figure 4 shows similarly plotted curves 14 and 15 when 980 volts was applied continuously to similar bodies. These curves again show that similar saturation occurred in still less time (about 600 seconds, or about 10 minutes).

It is therefore evident that the observed saturation in the resulting permanent piezo-electric effect is produced in less time as the polarizing voltage is increased, so long as the polarizing voltage is not so high as to break down the insulating qualities of the body severely and cause it to become conductive by dielectric breakdown or sparking.

Figure 5 shows a composite of such results in such a way as to indicate that there is a rather well defined minimum polarizing voltage, about 100 volts (2500 volts per centimeter), below which rapidly decreasing permanent piezo-electric effects are produced, and that at maximum usable voltages the best permanent effects are obtained. In the curve 16 in Figure 5 the actual coupling factor "K," as defined above, measured five minutes after removal of the forming voltage is plotted as ordinate against the amount of forming or bias voltage plotted as abscissa, each bias voltage having been applied long enough to reach the saturation described above.

It is evident from this curve 16 that better permanent piezo-electric effects are obtained with larger bias voltages applied for the proper length of time.

It should be noticed that the piezo-electric ef-

fect thus produced continues to decrease longer than five minutes after the bias voltage is removed, but that all rapid changes are complete within five minutes, and especially that changes taking place later are always a decrease in piezo-electric effect over a long period which is substantially proportioned to the first activity in all cases.

The curve 16 was made from measurements made on the same bodies subjected first to low forming voltages and later to higher voltages. In order to determine the effect of prior electrical history of the bodies, new readings were made, which are shown plotted as curve 17 in Figure 5, in which newly made bodies were used for each point of the curve. In other words, a body polarized at 1000 volts for a point on the curve at the 1000 volt abscissa had never previously been polarized at any other voltage. This curve shows that such previously unpolarized bodies produce substantially more output, or in other words, are more "active," when polarized at voltages above about 500 volts (12,000 volts per centimeter) and become quite highly active when polarized at 1000 volts (about 25,000 volts per centimeter).

It is therefore preferred to polarize polycrystalline aggregate bodies which have never before been polarized at about 25,000 volts per centimeter for at least the saturation time, in order to obtain the maximum possible permanent piezo-electric effect, although somewhat less activity is secured at lower voltages and with bodies which have some significant electrical history.

It is, in fact, preferred in order to realize the maximum permanence of the piezo-electric effect to form the bodies in such a manner for about 20 hours.

In applying the forming voltage to these bodies, it has been found convenient, since their internal resistances when active are very high, to supply the voltage from dry batteries through a high resistance of, for example, about ten megohms. The voltages indicated are, however, always measured across the electrodes of the body. In so applying polarizing voltage it has been observed that some of the bodies which break down internally and have therefore relatively low internal resistance are of little use, and that others which retain the highest internal resistance are somewhat less active than those whose internal resistance drops somewhat during the forming period. This phenomenon is not fully understood and is set forth here merely as an aid in the manufacture of the devices.

As an indication of the permanence of bodies so constructed, measurements were made of output for about three weeks, after polarization, the bodies being maintained at a temperature of 65 degrees C. The results of such measurements are shown in Figure 6 in which mechano-electrical coupling coefficient "K" is plotted as ordinate against time as abscissa.

In Figure 6, curve 18 shows the decrease in activity as a function of elapsed time since polarization, and indicates that no substantial decrease in activity occurs subsequent to the fourth day following polarization. This curve incorporates data taken from observation made of bodies whose internal resistance dropped somewhat during polarization.

Curve 20 is similar to curve 18, but was made from measurements of bodies whose internal re-

distances remained high during the forming period.

Thus it may be seen that the activity of bodies whose internal resistance dropped somewhat during polarization is considerably higher than that of bodies whose internal resistance remained high; in both cases, the decrease in activity approaches an asymptotic value within the first week following polarization.

It has been found by experimentation that bodies maintained at room temperature during the aging period approach substantially the same asymptotic value, but at a much slower rate.

The artificial polycrystalline aggregate disclosed herein has characteristics distinguishable from those of natural crystals such as Rochelle salt or quartz crystals in that such natural crystals have a finite number of planes of symmetry around the electrical axis whereas with the presently disclosed material there is a common axis of cylindrical symmetry with respect to its mechanical and electrical properties and there are an infinite number of planes of symmetry.

While the piezo-electric effect which appears in bodies formed in accordance with this invention is by no means fully understood, it is thought that the individual crystals in the polycrystalline aggregate are of a form which is symmetrical above transition temperature, and asymmetrical about their centers below that temperature, and that the application of a continuous electric field through such aggregate for a sufficiently long time tends to orient the slight asymmetry of the crystals so that their "electric" axes become most nearly parallel to the direction of the applied unidirectional field, although the individual crystals evidently do not move in the aggregate.

It is important to note that the direction and sense of the unidirectional applied electro-static field must remain the same throughout the process of formation, and, as explained above, it is polarized or formed to the saturation point.

While particular embodiments of the present invention have been shown and described and particular processes explained, it will be obvious to those skilled in the art that changes and modifications may be made without departing from this invention in its broader aspects and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of this invention.

I claim:

1. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at a temperature below said transition temperature; producing a unidirectional electrostatic polarizing field in said aggregate; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

2. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at a temperature below said transition temperature; producing in said aggregate a unidirectional electrostatic po-

larizing field of a value between about 2500 volts per centimeter and the breakdown value for said aggregate; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

3. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at a temperature below said transition temperature; producing in said aggregate a unidirectional electrostatic polarizing field of the order of 15,000 volts per centimeter; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

4. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at a temperature below said transition temperature; producing in said aggregate a unidirectional electrostatic polarizing field of the order of 25,000 volts per centimeter; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

5. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at a temperature below said transition temperature; without previous application of any electric field, producing a unidirectional electrostatic polarizing field in said aggregate; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

6. The process of producing a permanent piezo-electric effect in a solid polycrystalline aggregate of crystals individually possessing piezo-electric properties below a predetermined transition temperature and losing said properties above said transition temperature, which process comprises: maintaining said aggregate at normal room temperature; producing a unidirectional electrostatic polarizing field in said aggregate; and maintaining said polarizing field for a substantial time at least approaching that required for saturation of said effect.

WALTER L. CHERRY, Jr.

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Disclaimer

2,538,554.—*Walter L. Cherry, Jr.*, Northbrook, Ill. PROCESS OF PRODUCING PIEZOELECTRIC TRANSDUCERS. Patent dated Jan. 16, 1951. Disclaimer filed Dec. 22, 1951, by the inventor and the assignee, *Zenith Radio Corporation*.

Hereby enter this disclaimer to claims 1 to 6 inclusive of said patent.
 [Official Gazette February 19, 1952.]