May 20, 1947. C. CHILOWSKY 2,420,652

METHOD AND APPARATUS FOR MAKING ARTIFICIAL PIEZOELECTRIC ELEMENTS

Filed April 8, 1944

Fig. 1.

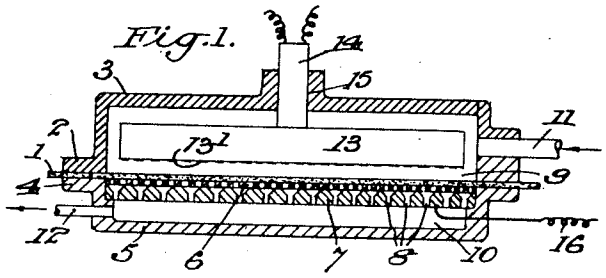


Fig. 2.

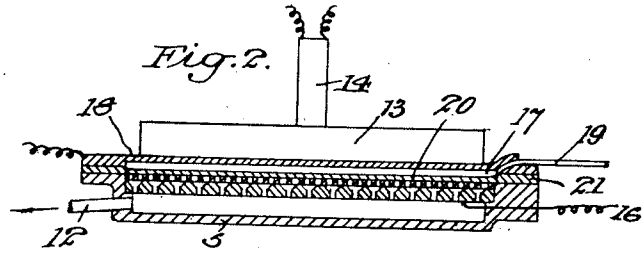


Fig. 3.

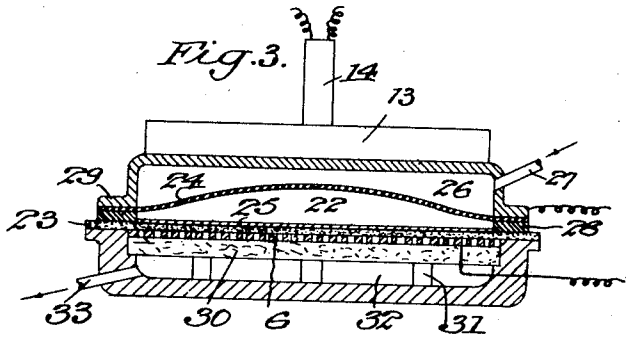


Fig. 4.

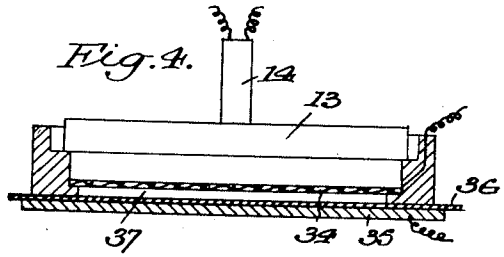
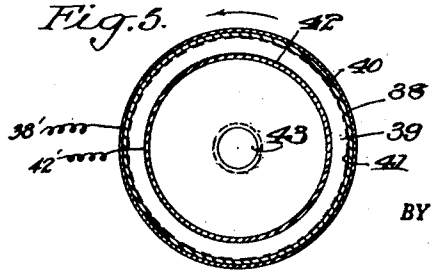


Fig. 5.



INVENTOR.
Constantin Chilowsky
BY
Brown & Seward
ATTORNEYS

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METHOD AND APPARATUS FOR MAKING ARTIFICIAL PIEZOELECTRIC ELEMENTS

Constantin Chilowsky, New York, N. Y.

Application April 8, 1944, Serial No. 530,137

29 Claims. (Cl. 171—327)

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This invention relates to a method and apparatus for making artificial piezoelectric elements, particularly by the use of an electro-mechanical procedure to orient finely divided particles of piezoelectric material suspended in a fluid medium, the material and medium being then substantially separated and the material compacted and solidified into a useful form of piezoelectric element.

In a copending application filed April 17, 1943, Serial No. 483,514, applicant has described a process of preparation of "piezoelectric" material, according to which fine powdered piezoelectric crystals are incorporated in a mass of plastic (or other) material, which may be in a liquid, semi-liquid, or pasty state, and which can be polymerized or solidified. This mixture, in the form of layers or plates, is subjected to the simultaneous action of mechanical oscillations and of an alternating electric field, synchronized in frequency and in phase, in order to obtain and to maintain common orientation of the mass of piezoelectric crystals, suspended in the mixture, with respect to the average or predominant direction of their piezoelectric axes. The mixture is subjected at the same time to a process of polymerization or solidification, finally fixing and immobilizing the particles by such solidification, thereby obtaining a solid substance with piezoelectric properties.

This process has a disadvantage in that the orientation and polymerization take place simultaneously, and that the material, subjected to the action of the electric field and of the mechanical vibration, must be at the same time maintained under conditions of temperature, etc., assuring polymerization up to the moment of sufficient solidification, which complicates the operation. At the same time, duration of the application of the electrical and mechanical oscillations may be materially extended by the conditions of polymerization, generally requiring considerable time.

The present invention has for an object the elimination of these disadvantages, and the provision of a procedure in which a wide variety of materials may be used to make elements having a high piezoelectric modulus, comparable, if necessary, to that of natural crystals, and capable of substitution therefor in any of their normal uses.

According to this invention, a plurality of piezoelectric crystals (or a powder of such crystals) are incorporated in a supporting material which may be liquid, semi-liquid or in the form of a paste, the proportion of the crystals to the

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amount of the liquid being generally sufficiently small so that the crystals do not touch each other and retain freedom of movement in the liquid (referred to herein as "fluid medium").

The material thus prepared is passed through a filter of such porosity that the liquid, semi-liquid or paste passes through, but the solid particles of the piezoelectric crystals remain on the surface of the filter. The layer of the liquid or paste on the filter is subjected during the filtering to simultaneous action of mechanical oscillations and of an alternating electric field, synchronized in frequency and in phase, as described in the above-named patent application. The half wave length of mechanical oscillations in the liquid or paste should be greater than the thickness of the layer being deposited, and the distance between electrodes producing the electric field should preferably be less than the half wave length of said field. The simultaneous mechanical and electrical action orients the piezoelectric crystals in the fluid medium and maintains the orientation during the process of filtering. The crystals settle on the surface of the filter, one above the other, all of them uniformly oriented, so that on the surface of the filter is formed a compact layer of a filtrate in which the crystals, uniformly oriented, touch each other and are firmly maintained in such an orientation mechanically by the close contact between the particles, established during their deposition on the filter. Such a layer of the filtrate, which can be finally consolidated by certain mechanical compression and can, eventually, be removed from the filter plate, is subsequently subjected to a process of definite consolidation whereby the liquid, filling spaces between the crystals, is solidified, so that the product represents a solid plate with piezoelectric properties.

Other methods for the electric orientation of finely-divided piezoelectric material suspended in a fluid medium may be used in connection with the herein described procedure of concentration and separation. For instance, orientation of such material can be effected by simultaneous action of constant pressure applied to the liquid containing the suspension and of a constant electric field, in the case of certain piezoelectric crystals which show polarization even when submitted to homogeneous compression in a liquid. The compression of the fluid can be obtained in any suitable manner as, for instance, by means of a pump or other compressing device supplying the fluid to the apparatus, in combination with the use of a restricted outlet from the apparatus, if necessary.

When the sedimentation of the material is accomplished by centrifugal means the compression may result directly from the action of centrifugal force on the fluid with its suspension.

It is also possible in certain cases to submit the fluid with its suspended material to heating or to cooling, which produces in certain materials a pyroelectric polarization, the fluid and its suspension being simultaneously subjected to the action of a constant electric field in order to orient the suspended piezoelectric crystals. This orientation will be maintained during the concentration of the suspended material (by filtration or otherwise) until the particles of the material come into direct contact in the deposited layer so that they will maintain themselves mechanically in their oriented position. The heating or cooling of the fluid may be done either in the chamber where the concentration is to be effected or outside of the chamber before the fluid is introduced into the chamber.

In a preferred procedure the fluid medium used will be of such a type that it can form a plastic material by polymerization. By submitting the filtrate with its impregnating liquid to a process of polymerization (which can comprise the application of suitable temperature, pressure, and other conditions according to the material being used) a piezoelectric material is obtained. Such polymerization can be effected independently of the action of the alternating electric field and of the mechanical oscillation, whose duration is necessarily limited only to the short period of filtration and of formation of the filtered residue. This filtration can take place under any desired compression or suction and therefore can be effected with any desired rapidity. This operation, generally, may be quite independent of the subsequent polymerization.

A second important advantage of this process resides in the fact that a piezoelectric body thus formed will have the density of the piezoelectric crystals brought to a maximum, the crystals touching each other and being even brought into a close engagement with each other. The wasted space, occupied by an inactive plastic mass, will be reduced to a minimum, and the piezoelectric modulus of the material will also be brought to a maximum. In the process where polymerization and orientation are simultaneous, the crystals must remain spaced from each other without actual contact between them.

The present method is also applicable to a case where the supporting liquid is melted by heat and is later solidified by cooling instead of polymerization. It is also possible to use a supporting liquid which becomes solidified by drying or by evaporation.

Generally, in order to render the process of orientation more efficient, the supporting liquid selected is sufficiently viscous, and sufficiently high frequencies of electric field must be used. This is particularly so in the case of piezoelectric crystals which show no appreciable polarization when submitted to homogeneous pressure from all directions in a liquid. In such cases, for instance, paraffin oil of appropriate viscosity may be used as the supporting liquid. For types of crystals which show electric polarization even under homogeneous pressure, high viscosity and frequency are not indispensable, and constant pressure and electric fields may be applied as described above. The supporting liquid is an insulator, capable of supporting electric fields. In certain cases the original liquid may not be polymerizable, and upon completion of filtration it may be entirely eliminated from the layer of the filtrate, which may be then impregnated with a polymerizable liquid, which, after polymerization, will form a solid product. In this manner it is possible to select for the orientation a liquid most suitable for this purpose and to replace it subsequently with a suitable polymerizable substance.

In one important modification of the process, at least two powders are added to the liquid: One consisting of piezoelectric crystals, and the other, which will serve as a final support for the crystals, by filling their interstices. The liquid containing these two powders is used only as a temporary support and is finally removed so that the final piezoelectric product consists only of the two suspensions; piezoelectric crystals (active powder) and supporting inactive powder. The inactive powder is used in a proportion sufficient (in relation to the active powder) for filling all the pores between the active particles. Any liquid which is an electric insulator and which does not dissolve the two suspensions may be used as temporary support. By submitting the liquid with the two suspensions to a process of filtration as described, and superimposing mechanical vibrations with alternating electric field, a compact layer of the filtrate is obtained, containing uniformly oriented piezoelectric crystals, from the point of view of their piezoelectric properties, packed with the filling or supporting (inactive) powder. Subsequently the liquid is removed from the layer of the filtrate by suitable means, such as by the pressure of a gas, by washing out, drying, evaporation, extraction by a solvent, extraction with volatile liquids, compression, etc. The layer of filtrate, freed from the liquid, is compressed at a temperature of softening or fusion of the inactive powder which fills the spaces between the crystals. After cooling, the product will represent a compact mass, without material discontinuities or pores, the crystals being entirely united with the filling material. During this operation of compression, the crystals largely retain their initial common orientation so that the product will be piezoelectric. (In certain cases, with suitable materials, it is possible to unite the materials by using very high pressures alone; or only by heating without additional pressure to a temperature of fusion of the passive material, the envelopment of the material being effected by capillary forces.)

The modification just described makes it possible to use plastic substances in powdered form, thereby generally eliminating the actual process of polymerization. On the other hand, this modification makes it possible considerably to enlarge the variety of piezoelectric bodies which can be formed. Also, for instance for ultrasonic frequencies, it is possible to use appropriate plastic material as a passive powder. The layer of filtrate, freed from the liquid, is compressed between heated plates to form a piezoelectric plate. It will be understood that the filling material must be of such nature that it may be softened below the temperature at which the crystals lose their piezoelectric qualities.

The inactive powder can also be of a material fusible at a high temperature and supporting very high mechanical frequencies, for instance glass powder or powder of Pyrex glass, or any other material the melting point of which is lower than the temperature at which the active powder loses its piezoelectric qualities. The ac-

tive powder in these cases may be, for instance, piezoelectric quartz or tourmaline powder. In this case the filtrate, after being freed from the liquid, is heated to a temperature of fusion or softening of the glass or other inactive material, and after compression and heating, a piezoelectric body is obtained with crystals, embedded in glass (or such other material), mechanically continuous, capable of vibrating at very high frequencies and suitable for fabrication in plates of large linear dimensions.

By this proceeding a substtiute for natural piezoelectric quartz may be obtained, in any appropriate form, for instance: Plates of large linear dimensions; thin plates of large linear dimensions, which can be cut in small plates (as for quartz stabilizers for high frequency current); quartz plates for stabilizers, in desired thickness and linear dimensions, which will only require a final adjustment of their frequency. This final adjustment of thickness and consequently of frequency can be done either mechanically, or by the special proceeding of vapour deposit described in applicant's copending patent application, Serial No. 520,275, filed January 29, 1944. Said application discloses a procedure of supporting the plates (semi-finished to a thickness less than that finally desired) in a vacuum chamber, projecting against the plates a jet of vaporized metal such as aluminum which is deposited on the surface of the plates, automatically measuring the thickness of the combined plate and deposited metal, and automatically arresting the deposit when the desired thickness has been reached; the finished plate being thereupon moved out of the line of the jet and another plate being brought into position for treatment. In the case of adjustment by vapour deposit all the procedure of fabrication of piezoelectric quartz stabilizers can be accomplished with the elimination of many of the presently required mechanical operations.

In certain cases it can be also provided that the filtrating liquid, forming a provisional support, will only contain the powder of piezoelectric crystals, for instance of piezoelectric quartz. The layer of filtrate of these oriented crystals, after eliminating of the supporting liquid, will consist only of oriented piezoelectric quartz crystals. This layer in the required thickness will be submitted to a high mechanical pressure, at the temperature approaching the melting or softening temperature of these crystals.

Thus, an artificial piezoelectric body composed entirely of piezoelectrically oriented quartz (or other crystals) may be obtained.

In the instances described above, the preparation of piezoelectric materials for high frequency resonance stabilizers, consisting, for instance, of powdered quartz or tourmaline crystals, and of a generally non-crystalline or amorphous powder, such as glass or fused quartz, it is desirable to take special measures for reducing variations of the natural frequencies of the prepared plates with changes of temperature. For this purpose powdered Pyrex can be used (as already mentioned), this material having a very small coefficient of thermal expansion. If preferred, the proportion of the powdered crystals can be reduced with reference to the Pyrex powder. In the resulting piezoelectric plate with Pyrex, the natural frequency will be determined mainly by the thermo-mechanical properties of Pyrex, the embedded piezoelectric crystals acting mainly as exciters of mechanical oscillations. The variations of the natural frequency with changes in temperature will be considerably reduced.

Such temperature effect can be still further reduced by the use of amorphous fused quartz as the inactive powder, whose thermal coefficient of expansion is exceedingly small. The preparation, however, is more difficult in this case.

In the foregoing cases where the oriented piezoelectric crystals are finally incorporated in an amorphous substance which (as with Pyrex glass or fused quartz) has a coefficient of thermal expansion much smaller than the crystals, the cooling of the plates is preferably conducted under high compression, and very slowly.

The reduction of the thermal coefficient of frequency of ordinary quartz stabilizers is obtained by special cutting in an oblique direction with reference to the piezoelectric axis, thus causing the quartz to vibrate obliquely (with all the inconveniences of such an oblique oscillation). On the other hand, in the foregoing described instances, a satisfactory reduction of the thermal coefficient results from the low coefficient of the substance of the plate itself. The plate will, however, vibrate normally at the surface (through the thickness) with all the advantages of such a vibration. This will compensate, at least partially, for the decrease of amplitude caused by the above reduction of the proportion of the active material (piezoelectric crystals) with reference to the filling material.

The described process of orientation by filtering makes it possible to produce, for stabilizers, individual plates of definite thicknesses. This can be accomplished by introducing accurately weighed quantities of the active and inactive powders. After filtering through a filter of a suitable area, the remaining filtrate will have exactly the same weight, and consequently, at the end of the preparation, will produce a piezoelectric plate of the same exact weight and, therefore, of dimensions closely approaching the requirements.

Under certain conditions the liquid containing the two suspensions is not removed after orientation of the crystals, as when a liquid is used which can be solidified and subsequently decomposed by heat. A double suspension can be made, for instance, in a thick solution of collodion or other nitro-compounds. After filtering, the collodion impregnating the remaining layer of filtrate is solidified by evaporation and the solid plate thus formed is transferred into a heated press. The collodion will be decomposed by heat and the residue, compressed with the application of heat, will form a piezoelectric film. By suitably modifying the operation, it is also possible to use Celluloid or the like in place of collodion.

Melted substances, such as melted wax or rosin, can be used as a temporary support and vehicle liquid. Under a hot press the wax will melt and evaporate. In general, liquid bodies with temperatures of melting and vaporization below the temperature of fusion of the inactive filling powder, can be used as a temporary support, enabling the filtered residue to be handled and transferred in the form of compact plates.

It is also provided that the manipulation and transfer of the layers of filtrate can be effected by mechanical means and by special arrangement of the filtering surfaces. More particularly, it is possible to manipulate and to transfer the layers of filtrate on thin filters of paper, or the like which have been used for filtration, and

which are finally destroyed in the operations of heating and polymerization.

In a modified process it is provided that the formation of a compact layer of oriented crystals, or oriented crystals with an inactive powder, from a liquid containing these suspensions, can be effected by the action of centrifugal force on the particles, suspended in the liquid; or even in certain cases this layer can be formed by the action of gravity, in the form of a sedimentary deposit. In these two cases the layer of the liquid with the suspension is subjected, in its portion near the surface on which the deposit is formed, to the simultaneous action of mechanical vibration and alternating electric field, synchronized in frequency and in phase, as already described. The filtration can also be combined with the centrifuging of the liquid with its suspension.

In the described process of the progressive formation of the layer of the filtrate, the oriented crystals, deposited by the filtering liquid, are subjected at the moment of contact with the previously formed deposit, to certain irregular deviations from their correct orientation. Such deviations of orientation which reduce the final piezoelectric modulus of the deposited layer are due to exterior physical irregularities of the crystals. For reducing or eliminating such an undesirable phenomenon, it is proposed to subject the powdered piezoelectric crystals, prior to their inclusion in the liquid, to a mechanical treatment for homogenizing dimensions of the particles, and particularly for imparting to them as nearly as possible a spherical shape. This can be effected by known methods of "rolling" the crystal particles between two parallel surfaces, similar to the known method used for obtaining sphericity of the balls used for ball bearings. The crystals, thus reduced to a spherical shape and homogenized as to their dimensions, will not suffer any deviations from their common homogeneous orientation upon coming in contact with the already formed layer of crystals, and the piezoelectric modulus of the obtained body will attain its maximum, compatible with the density of the piezoelectric material.

A practical embodiment of the invention is shown in the accompanying drawing in which:

Fig. 1 represents a vertical median section of a filtering and orienting apparatus in which a mechanical vibration generator is located within the upper filter chamber;

Fig. 2 represents a vertical median section of a modified form of apparatus in which the mechanical vibration generator is located on top of the upper filter chamber;

Fig. 3 represents a vertical median section of another modified form of apparatus adapted for the introduction of a measured quantity of material to be filtered;

Fig. 4 represents a vertical median section of a form of orienting apparatus adapted to operate by sedimentation; and

Fig. 5 represents a section perpendicular to the axis of a centrifugal type of apparatus.

Referring to Fig. 1, which shows an apparatus adapted for use with a liquid vehicle having finely divided piezoelectric material and inactive material suspended therein, a thin filter 1 of a suitable filtering material (for instance, paper, cotton, agglomeration of compressed powder, etc.) permitting passage of the liquid but retaining the crystals and particles of the inactive powder is fastened at its edges between a flange 2 of an upper cover 3, and the flange 4 of the lower receptacle 5. Under the filter 1 is a finely perforated sheet or screen 6, resting on a rigid supporting grid or plate 7, firmly fitted in the lower receptacle 5. The grid or plate 7 is provided with a number of conical or funnel-shaped openings 8, enlarged toward the upper side.

The perforated sheet 6 and the plate 7 form a solid support for the filter 1, permeable to liquids, and mechanically resisting any difference in pressure between the contents of the upper chamber 9 and the lower chamber 10. The liquid with the suspension is introduced under pressure into the chamber 9 by a tube 11, and the liquid, after passing through the filter and being freed from the suspension, is removed from the chamber 10 through a tube 12. Pressure may be applied for this purpose through the tube 11 or suction through the tube 12, or both. A generator of mechanical vibration 13 is shown in full lines (not in section), as is also its supporting stem or shank 14 which passes through a gas-tight bearing 15 in the cover 3. If the applied frequency is supersonic, it is possible to use a quartz supersonic generator of a sandwich type; or, for very high frequencies, a quartz generator without armature. For lower frequencies a mechanical vibrator can be used, actuated by a liquid or gas under pressure. Electric leads of the generator 13 (if present) may pass through the shank 14. Conduits for a gas or liquid under pressure, if the generator is operated by them, may also pass through the shank 14. An electric alternating field is applied to the layer of liquid and suspended material upon the filter 1, by the metallic surface 13' of the vibrator 13 at one side, and by the metallic perforated sheet 6 (through a lead 16) at the other side. It will be evident, however, that other suitable arrangements of parts for filtering can be used.

The liquid containing the suspension should be an insulator, having a suitable viscosity. After formation on the filter 1 of a layer of the oriented filtrate of a desired thickness, the rest of the liquid is exhausted from the chamber 9, if any remains, then the cover 3 is removed, and the filter 1 with the deposited layer of filtrate is removed to be placed in an apparatus for polymerization. The perforated sheet or screen 6 may also be removed with the filtrate to facilitate the manipulation thereof by providing a more firm support.

In Fig. 2 is shown a modified arrangement in which the generator 13 for mechanical vibrations is placed outside the chamber 17, being applied to the cover 18 for transmitting the vibrations through the cover to the liquid layer in the chamber 17. The generator 13 can be also made integral with the cover 18 by cementing or soldering. The chamber 17 may be much reduced (compared to chamber 9, Fig. 1) and made just sufficient for containing the desired layer of the oriented filtrate. A filling tube 19 permits an almost complete evacuation of any excess liquid prior to the opening of the device. The filter 20 is shown as having a peripheral reinforcement 21 which may also serve as insulation between the cover 18 and the lower parts, for the establishment of the alternating electric field.

In Fig. 3 is shown another modification in which the liquid containing suspended materials is introduced beforehand in a required quantity for the formation of a desired layer in a chamber 22 formed between a thin filter 23 (resting on a perforated electrode sheet 6) and a flexible membrane 24, for instance, of rubber or other

suitable material. A thin layer 25 of the oriented filtrate is shown beginning to be deposited. A suitable liquid or gas is introduced under pressure into the chamber 26 by a tube 27. A supplementary gasket 28 of a thickness approximately equal to the thickness of the desired filtrate can be placed between the flange 29 and the periphery of the filter 23. Means for clamping the parts together is not shown on the drawing, being known and self evident. The filter 23 and sheet 6 may rest on a support 30 of strong but very porous material which, in turn, is supported on columns or walls 31 in the exhaust chamber 32. The perforated sheet 6 forming an electrode for the electric field can, if desired, be placed under the porous support 30, the filter in this case resting directly on the support 30. The filtering of the liquid contained in the chamber 22 is expedited by pressure applied at 26 by means of tube 27 (or by suction applied at 32 by means of tube 33) the membrane 24 spreading over the filtrate.

In Fig. 4 is shown a form of device in which the layer of oriented crystals is formed by sedimentation under slow action of the force of gravity. The liquid with suspended materials is traversed by mechanical oscillations from the generator 13; 34 is a wire gauze sheet or grill forming one of the electrodes of the alternating electric field, the other electrode being formed by the support 35. 36 is a supporting plate, preferably of insulating material, for facilitating handling the deposit. One of the electrodes can be also formed by the provision of a metallic surface 13' on the generator 13 (as in Fig. 1) instead of by the grill 34. In this case the solid particles will settle in the space 37 between the electrodes, where they are caused to assume their desired orientation as previously explained.

In Fig. 5 is shown diagrammatically in section a device in which the oriented deposit is formed by centrifugal force. In this figure 38 denotes the outer cylindrical wall of a centrifugal apparatus rotating at a high speed, filled with a liquid with suspended materials in the space 39. 40 is a removable support for the deposited layer, for instance, a fixed sheet, on which the suspension is deposited by the centrifugal force. The broken line 41 indicates a deposit of oriented crystals in the process of formation. 42 is a cylindrical wall of a slightly elastic material (such as ebonite), susceptible to radial vibrations. It forms the outer side of a radial mechanical vibrator, the vibrations of the wall 42 being caused by variations in pressure, for instance, of the hydraulic pressure within the space enclosed by the wall 42, the rapid variations in pressure being transmitted, for instance, through the axial opening 43 by means of a hydraulic piston (not indicated on the drawings) vibrating with a suitable frequency. After centrifuging of the deposit, it is removed on its support 40 and may then be flattened out, polymerized, and cut into desired smaller parts. If a cylindrical piezoelectric element is desired the polymerization may be effected while the deposit and its support are still in cylindrical form. In following the centrifugal procedure just described the orientation of the crystals is assured by the establishment of an alternating electric field between the parts 38 and 42; if the wall 42 is non-conducting it may be metallized on the surface to form an electrode. The leads 38' and 42' connect the wall 38 (serving as an electrode) and the metallized surface of the wall 42 to a suitable source of alternating current, the connection being maintained, for instance, through a conventional brush and collector ring arrangement, not shown.

It will be understood that various changes may be made in the construction, form and arrangement of the several parts and in the steps of the method without departing from the spirit and scope of my invention and hence I do not intend to be limited to the particular embodiment herein shown and described, but what I claim is:

1. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely divided piezoelectric material, suspending said material in a fluid medium, orienting said material with respect to its piezoelectric axes, and substantially separating said material and medium while the material is maintained in its oriented condition.

2. The method of making an artificial piezoelectric element according to claim 1 in which the material and medium are separated by filtration.

3. The method of making an artificial piezoelectric element according to claim 1 in which material and medium are separated by sedimentation.

4. The method of making an artificial piezoelectric element according to claim 1 in which the the material and medium are separated by centrifugal sedimentation.

5. The method of making an artificial piezoelectric element according to claim 1 in which the quantity of piezoelectric material is predetermined in conformity with the desired dimensions of the element being produced.

6. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely divided piezoelectric material providing a quantity of finely divided filling material, suspending said materials in a fluid medium, orienting said piezoelectric material with respect to its piezoelectric axes, and substantially separating said materials and said medium while the piezoelectric material is maintained in its oriented condition.

7. The method of making an artificial piezoelectric element according to claim 1 in which the quantity of piezoelectric material and the quantity of filling material are predetermined in conformity with the desired dimensions of the element being produced.

8. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely divided piezoelectric material, suspending said material in a fluid medium, orienting said material with respect to its piezoelectric axes, concentrating said oriented material to establish direct physical contact between the particles, whereby the orientation thereof is maintained, removing the excess fluid medium, and consolidating the oriented piezoelectric material.

9. The method of making an artificial piezoelectric element according to claim 8 in which the fluid medium is adapted to be solidified and to remain solid under normal conditions of use, and in which a residue of said medium fills the interstices of the concentrated material and is solidified to consolidate said material in a physically continuous mass.

10. The method of making an artificial piezoelectric element according to claim 8 in which the fluid medium is a plastic adapted to be solidified and to remain solid under normal conditions of use, and in which a residue of said medium fills the interstices of the concentrated material and

is solidified to consolidate said material in a physically continuous mass.

11. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely-divided piezoelectric material, providing a quantity of finely-divided plastic material, suspending said materials in a fluid medium, orienting said piezoelectric material with respect to its piezoelectric axes, concentrating said oriented material and plastic material to establish direct physical contact between the particles, whereby the orientation thereof is maintained, removing the fluid medium, and consolidating the piezoelectric and plastic materials in a physically continuous mass.

12. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely-divided piezoelectric material, providing a quantity of finely-divided amorphous material having a high melting point, orienting said piezoelectric material with respect to its piezoelectric axes, concentrating said oriented material and amorphous material to establish direct physical contact between the particles, whereby the orientation thereof is maintained, removing the fluid medium, and consolidating the piezoelectric and amorphous materials in a physically continuous mass by the use of suitable temperature and pressure.

13. The method of making an artificial piezoelectric element according to claim 12 in which the amorphous material is a glass, and in which the consolidation of the materials includes softening of the glass without materially disturbing the orientation and composition of the piezoelectric material.

14. The method of making an artificial piezoelectric element according to claim 12 in which the amorphous material is a Pyrex glass, and in which the consolidation of the materials includes softening of the glass without materially disturbing the orientation and composition of the piezoelectric material.

15. The method of making an artificial piezoelectric element according to claim 12 in which the piezoelectric material is quartz or tourmaline, the amorphous material is a glass, and in which the consolidation of the materials includes softening the glass without materially disturbing the orientation and composition of the piezoelectric material.

16. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely-divided piezoelectric material, suspending said material in a fluid medium, submitting said suspension to the simultaneous and synchronized action of mechanical oscillations and an alternating electric field, whereby said material is oriented with respect to its piezoelectric axes, and substantially separating said material and said medium while the material is maintained in its oriented condition.

17. The method of making an artificial piezoelectric element according to claim 16 in which the material and medium are separated by filtration.

18. The method of making an artificial piezoelectric element according to claim 16 in which the material and medium are separated by sedimentation.

19. The method of making an artificial piezoelectric element according to claim 16 in which the material and medium are separated by centrifugal sedimentation.

20. The method of making an artificial piezoelectric element which comprises, providing a quantity of finely-divided piezoelectric material, suspending said material in a fluid medium, submitting said suspension to the simultaneous action of varied pressure and of an electric field, whereby said material is oriented with respect to its piezoelectric axes, and substantially separating said material and said medium while the material is maintained in its oriented condition.

21. The method of making an artifical piezoelectric element which comprises, providing a quantity of finely-divided piezoelectric material, suspending said material in a fluid medium, submitting said suspension to the simultaneous action of varied temperature and of an electric field, whereby said material is oriented with respect to its piezoelectric axes, and substantially separating said material and said medium while the material is maintained in its oriented condition.

22. Apparatus for making an artificial piezoelectric element comprising, a chamber adapted to receive a suspension of finely-divided piezoelectric material in a fluid medium, means for concentrating the material and substantially separating said material and said medium while retaining the material in said chamber, means for polarizing the material in said suspension, and means for setting up an electric field in said chamber.

23. Apparatus according to claim 22 in which the polarizing means includes a generator of mechanical oscillations and in which the electric field is alternating in synchronism with the mechanical oscillations.

24. Apparatus according to claim 22 in which the polarizing means includes means for varying the pressure on the suspension.

25. Apparatus according to claim 22 in which the polarizing means includes means for varying the temperature of the suspension.

26. Apparatus according to claim 22 in which the separating means includes a filter adapted to pass the fluid medium and to retain the piezoelectric material.

27. Apparatus according to claim 22 in which the separating means includes means for concentrating the piezoelectric material adjacent to an interior surface of the chamber.

28. Apparatus according to claim 22 in which the separating means includes centrifugal means for concentrating the piezoelectric material adjacent to an interior surface of the chamber.

29. Apparatus according to claim 22 in which the chamber is provided with a flexible surface arranged to contact the upper surface of the suspension.

CONSTANTIN CHILOWSKY.