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April 22, 1969 A. R. MOORE 3,440,550
ZINC OXIDE MAXIMUM EFFICIENCY TRANSVERSE WAVE CRYSTALS AND DEVICES
Filed Oct. 25, 1966

FIG. 1

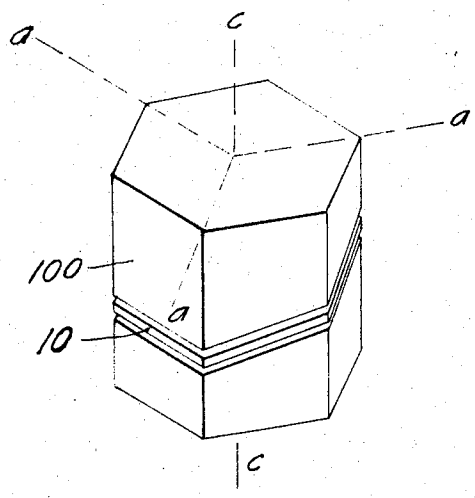


FIG. 2

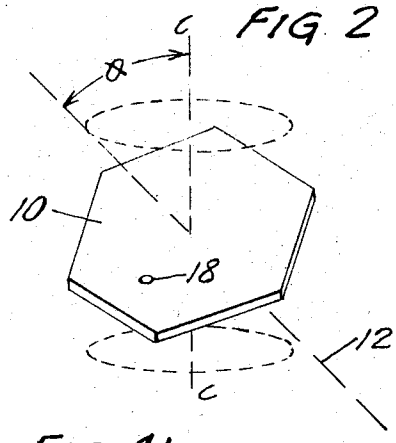


FIG. 4b

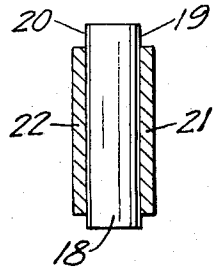


FIG. 4a

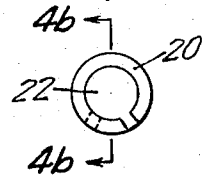


FIG. 3

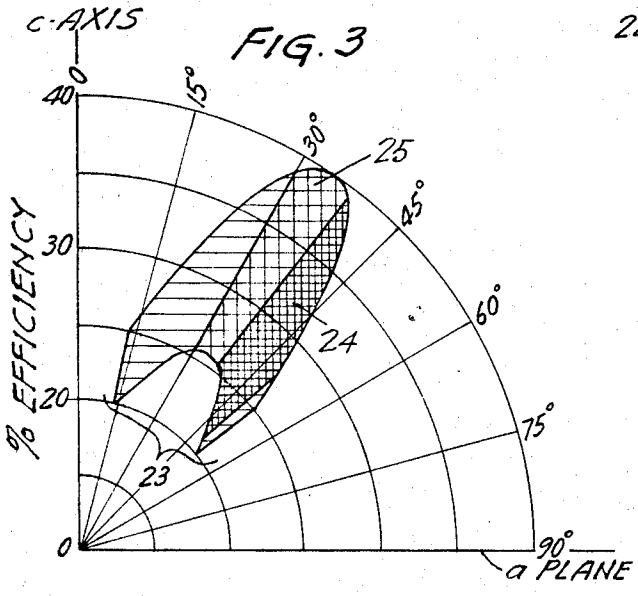


FIG. 5

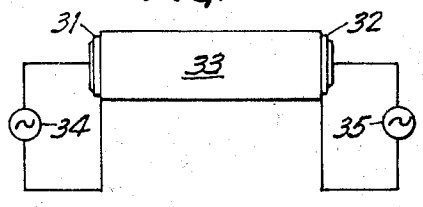


FIG. 6

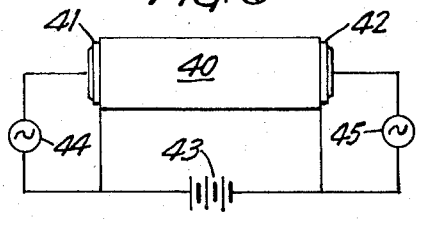


FIG. 7

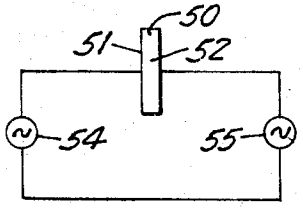
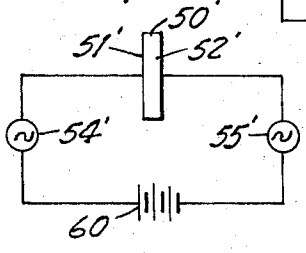


FIG. 8



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3440550
OR IN 330/5.5

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ZINC OXIDE MAXIMUM EFFICIENCY TRANSVERSE WAVE CRYSTALS AND DEVICES

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Int. Cl. H03f 3/04; H02n 1/00
U.S. Cl. 330—5.5 15 Claims

ABSTRACT OF THE DISCLOSURE

A piezoelectric device comprising at least one element consisting of a piezoelectric zinc oxide crystal having an axis passing through the crystallographic *c* axis and inclined at an angle theta relative to such crystallographic *c* axis wherein theta ranges from 13° to 53° and wherein the crystal has a resistivity between about 0.1 and 10^{12} ohm-cm. and means for making electrode contact with said element on at least one face is shown.

This invention relates to zinc oxide crystals which are capable of propagating acoustic transverse waves with an associated unexpectedly great and heretofore unrealizable electromechanical conversion efficiency, and to the improved devices made therefrom.

Zinc oxide, like quartz, is known to exhibit piezoelectric properties and to have excellent physical and chemical stability. Zinc oxide crystals exhibit the hexagonal wurtzite lattice structure with the oxygen ions arranged in closest hexagonal packing and the zinc ions occupying half of the tetragonal interstitial positions. Characteristically, the wurtzite atomic lattice structure has a crystallographic *a* plane and a crystallographic *c* axis. W. G. Cady in his book, "Piezoelectricity" (published by McGraw-Hill Book, Inc., revised edition, 1964), gives the elastic and piezoelectric constants for this crystal class and describes the piezoelectric modes present for the crystallographic axes.

Heretofore, it was known that zinc oxide single crystals were capable of propagating pure acoustic transverse waves if such crystals were electroded on opposed faces normal to the *a* plane. However, the electromechanical conversion efficiency of acoustic transverse waves so generated is about 20%.

I have now discovered, however, that zinc oxide crystals formed with certain new crystal orientations have coupling coefficients of acoustic transverse mode that greatly exceed the characteristic values obtained for those generated along the crystallographic *a* axis. The fact that these new orientations can be used for generating such efficient modes is unexpected and surprisingly advantageous since most electromechanical device properties are considered by those skilled in the art to depend upon the square of such coupling coefficients.

The present invention is better understood by reference to the following attached drawings taken together with the associated specification:

FIGURE 1 is an isometric drawing illustrating a section of a crystal of the present invention;

FIGURE 2 is an isometric view of the crystal shown in FIGURE 1 and illustrating the angle θ;

FIGURE 3 is a two-dimensional plot in polar coordinants showing the relationship between θ and the percent efficiency (coupling coefficient) for a crystal of the invention.

FIGURE 4 illustrates one embodiment of a device of the invention formed from a crystal of FIGURE 2,

FIGURE 5 illustrates schematically one embodiment of a delay line constructed using a device of FIGURE 4;

FIGURE 6 illustrates schematically one embodiment of an ultrasonic amplifier constructed using a device of FIGURE 4;

FIGURE 7 illustrates schematically one embodiment of a resonate cavity constructed using a device of FIGURE 4; and

FIGURE 8 illustrates schematically one embodiment of an electrical resonant cavity constructed using a device of FIGURE 4.

Referring to FIGURE 1 there is seen a section of a large crystal of zinc oxide which is designated in its entirety by the numeral **100**. Such a crystal can be grown by any one of the known processes for the production of single crystal zinc oxide. This crystal **100** is seen to have a crystallographic *c* axis and to have three crystallographic *a* axes which together define a crystallographic *a* plane.

A crystal wafer **10** of the invention can be made by any convenient procedure. For example, such a wafer **10** can be prepared from a crystal **100** by making two spaced parallel cuts through the crystal **100**, as follows: The crystal **100** is mounted conveniently on a conventional orientation jig (not shown) using wax or the like. An initial cut (not shown) is made approximately along a crystallographic *a* plane near one end or tip of the crystal using a precision wafering machine. This cut tip serves as an orientation guide by subjecting such tip to an X-ray crystal orientation procedure to determine the true direction of the *c* axis.

Next, the position of the orientation jig with the crystal mounted therein is carefully adjusted relative to the direction of cut by the blade in the precision wafering machine. One angle selected in this orientation process is the complementary angle to an angle theta (θ) (see FIGURE 2). Theta is the angle formed between the crystallographic *c* axis and the axis **12** of wafer **10**. The cut crystal axis **12** passes through the crystallographic *c* axis and is normal (or orthogonal) to the wafer **10** surface. Theta is measured relative to the crystallographic *c* axis. In accordance with this invention, values for the angle theta range from about 13° to 53° and thus, the complementary angle chosen ranges from about 37° to 77°. This relationship between the crystal axis **12** and the crystallographic *c* axis conveniently describes what is herein termed the CM series of crystal shapes (see FIG. 3).

A first preferred range of angles for theta in the CM series is from about 38° to 49° crystals because with these angles, crystals of the invention display minimum acoustic compression wave electromechanical coupling efficiency. This preferred range of values for theta describes what is herein termed the BM series of zinc oxide crystal shapes and is so labeled in FIGURE 3. A most preferred angle for theta, but one within the BM series, is about 44° because with this angle, a crystal displays the capacity to generate pure acoustic transverse waves.

A second most preferred range of angles for theta in the CM series is from about 30° to 38° because crystals with this orientation display a maximum magnitude of transverse coupling efficiency. This second angular range is called the DM series of zinc oxide crystal shapes and is so labeled in FIGURE 3. A most preferred angle for theta, but one within the DM series, is about 33° since such a crystal displays greatest transverse coupling efficiency.

In such CM series, the electric field propagation direction is required to be at an angle theta to the crystallographic *c* axis and to be parallel to such crystal axis **12** in order to obtain the indicated unexpected acoustic wave generation in accordance with the teachings of this invention. Reference to FIGURE 3 is helpful in determining the optimum relationship between the coupling efficiency and the angle theta in a given crystal. FIG-

URE 3 indicates the magnitude of the improved coupling efficiency achieved in a crystal constructed using the CM series in accordance with the teachings of this invention.

Continuing on with this example of preparing a wafer **10** from crystal **100**, if the initial cut through crystal **100** happened to have been made, for example, at an angle θ which is outside the X-ray machine range, it is sometimes desirable to make a second cut through crystal **100** after the jig has been duly positioned as described. However, after a satisfactory initial cut has been made, and after the crystal **100** in this jig has been thus fixed relative to the cutting direction of the blade in the wafering machine, the orientation jig is advanced a convenient distance, typically ranging from about one-half to four millimeters. A second cut through the crystal **100** is then made so as to separate and define the desired crystal wafer **10**. The actual thickness of a crystal wafer **10** is correlated to the end use to which the wafer is to be placed, in accordance with the teachings of this invention, and as hereafter more fully described.

The resulting crystal wafer **10** is preferably subjected to a conventional doping operation (see, for example, the doping procedures described by G. Heiland, E. Mollwo and F. Stockmann in "Solid State Physics," vol. 8, pp. 191–319, 1959). If the crystal wafer **10** does not already have a resistivity value between about 0.1 and 10^{12} ohm-cm., the crystal resistivity may be adjusted to a value within this range during the doping operation, the exact resistivity value for any given crystal wafer **10** being dependent upon the particular properties desired for the end use intended.

The resulting doped crystal wafer **10** is now conveniently subjected to a mechanical or chemical polishing operation whereby its opposed faces are polished to a predetermined desired extent, care being exerted to maintain the crystal orientation. Those skilled in the art will appreciate that smooth facial surfaces are desirable in electroding and in subsequent device performance.

Thereafter, the crystal wafer **10** is available for electroding or for mounting in a device. For example, referring to FIGURE 4, there is seen a crystal wafer **18** which has been conveniently formed from a crystal wafer **10**, by means of an ultrasonic cutter, grinder, chemical etch bath, or the like. Part *a* of FIGURE 4 represents a top plan view of wafer **18**, while part *b* thereof represents a vertical sectional view thru wafer **18** taken along the line *b*—*b* of FIGURE 4(*a*). The two opposed parallel faces **19** and **20** of the crystal wafer **18** have been appropriately masked and subjected to a vacuum vapor deposition operation so as to form thereon metal electrodes **21** and **22**. The use of vapor deposited electrodes is illustrative only, and any suitable method of forming electrodes on a crystal wafer **18** (such as electrolytic or electroless plating, sputtering, conductive pastes, and like) can be used.

Parallel faces are used on crystal **10** for illustrative purposes ony. It is sometimes advantageous to use crystals of this invention having non-parallel faces, or to use such crystals with a plurality of such faces and such electrodes to control production of particular acoustic waves or to control desired electric field propagation. Such constructions and other equivalent ones are within the teachings of the present invention. It will be appreciated that a crystal of the invention can be formed with any desired geometry so long as the angle theta is described.

Observe that, in general, electrodes such as **21** and **22** are each respectively so functionally associated with a crystal wafer **10** that the direction of electric field propagation is along the axis **12**. The axis **12** is related to the crystallographic *c* axis thru the angle theta. It is preferred to separate electrodes by a distance measured through the crystal by a distance greater than about 1 millimicron.

Referring once again to FIGURE 3, the plot there shown represents the generalized relationship between percent efficiency and theta in crystals of the invention. In a given crystal wafer, an exact statement of the relationship between theta and percent efficiency is not practical because, in given crystal wafer, such as crystal wafer **10** in this description, normal manufacturing variables inherently operate to induce variances in the product crystal. These manufacturing variances typically cause the resulting properties of a transverse wave generated in a given crystal of this invention to vary slightly from a desired or even optimum condition.

It will be appreciated that the plot shown in FIGURE 3 is based upon the use of an optimum or preferred shape for a crystal of the invention, as described above and as illustrated in FIGURE 2. The plot of FIG. 3 shows the entire CM series **23** with preferred BM series **24** and DM series **25**. For reasons similar to those just mentioned in reference to FIGURE 3, minor variations in any actual efficiency curve for a particular crystal of the invention tend to occur.

Surprisingly and unexpectedly, a crystal of this invention of the CM series displays greater electromechanical coupling efficiencies than is obtained by generating acoustic transverse waves along the crystallographic *a* plane. Also, surprisingly and unexpectedly, a crystal of this invention of the BM series having electrodes positioned thereon so as to create an electric field in the direction of the axis of such crystals is substantially incapable of propagating an acoustic compression wave concurrently with the generation or propagation of an acoustic transverse wave. It will be appreciated that herein the term "acoustic transverse wave" is synonymous with the term "thickness shear wave" or "thickness shear mode" and that the term "acoustic compression wave" is synonymous with the term "thickness extensional mode" or "thickness extensional wave."

FIGURE 5 is a schematic view of an ultrasonic delay line construction according to the teachings and references of J. H. Eveleth, "A Survey of Ultrasonic Delay Lines Operating Below 100 Megahertz" and G. P. Podrigue, "Microwave Solid-State Delay Lines," Proceedings of IEEE, vol. 53, No. 10, 1965. The transducers **31** and **32** of this delay line are mounted on a delay medium **33** of fused silica, CM series zinc oxide crystal of this invention, or the like, and in addition are each constructed using a CM series zinc oxide crystal of this invention, as shown in FIG. 4. Transducer **31** is connected to a signal source **34** and transducer **32** is connected to an appropriate receiver **35**. The resulting ultrasonic delay line has an unexpectedly superior bandwidth of transmission when compared to a similar delay line constructed so as to utilize a pair of transducers each utilizing a conventional single crystal of zinc oxide which transduces acoustic waves on the crystallographic *a* axis thereof.

Those skilled in the art will recognize that the optimum construction utilizes zinc oxide of the CM series as the delay medium, since acoustic impedance mismatch is thereby minimized.

FIGURE 6 is a schematic view of an ultrasonic amplifier constructed according to the teachings of U.S.P. No. 3,173,100. The amplifier utilizes a zinc oxide single crystal **40**, with an appropriate D.C. bias source **43**, as the amplifying medium. This medium is so oriented for interacting the D.C. field carriers with the acoustic wave that the direction of both the electric field propagation and the transverse acoustic wave propagation coincides with the CM series in a crystal of the invention. The D.C. bias creates an electric field magnitude governing the drift velocity of the responsive carriers. Each of the transducers **41** and **42** are adhered to crystal **40** and each is made using a CM series zinc oxide crystal prepared according to the teachings of this invention. Transducer **41** is connected to a signal source **44**, and transducer **42** is connected to an appropriate receiver **45**. The resulting ultrasonic amplifier has both unexpectedly superior bandwidth of transmission and signal gain compared to a similar amplifier constructed so as to utilize a conven-

tional single crystal of zinc oxide adapted to transduce acoustic waves on the crystallographic *a* axis thereof.

FIGURE 7 is a schematic view of a mechanical resonator constructed according to the teachings of W. P. Mason in his book "Electro-Mechanical Transducer and Wave Filters" (published by D. Van Nostrand Company, Inc., second edition). Metallic electrodes **51** and **52** are adhered to the resonator body **50**, which comprises a CM series zinc oxide crystal prepared according to the teachings of this invention. Electrode **51** is connected to an appropriate signal source **54** and electrode **55** is connected to an appropriate receiver **55**. The resulting mechanical resonator has unexpectedly superior bandwidth of transmission when compared to a similar resonator constructed so as to utilize a conventional zinc oxide single crystal adapted to transduce acoustic waves on the crystallographic *a* axis thereof.

FIGURE 8 is a schematic view of an electrical resonator constructed according to the teachings of E. L. Adler and G. W. Farnell in "The Effect of Acoustoelectric Interactions on the Electrical Impedance of a CdS Bar" (Doctoral thesis, McGill University, Montreal, 1965) and using a D.C. bias source **60**. Components in this device are similar to those in the device of FIGURE 7 and are accordingly numbered similarly except that prime marks are added thereto in each instance for convenience and clarity. This device is the combination of a mechanical resonator and an ultrasonic amplifier, as those skilled in the art will recognize. The resulting electrical resonator device has unexpectedly superior acoustic signal gains near the mechanical resonant frequencies of the crystal, compared to a similar resonator constructed utilizing a conventional zinc oxide single crystal adapted to transduce acoustic waves on the crystallographic *c* axis thereof.

The following examples of particular embodiments are provided to further describe the invention. Each example employs at least one CM series zinc oxide crystal prepared as described above in reference to FIGURE 2. Using these examples, devices may be constructed so as to operate on any part of the specified curves in FIGURE 3.

Example 1

The construction here is identical to that shown in FIGURE 5 and above described. Two crystal wafers of BM series zinc oxide crystal are used as transducers, each one having a resistivity of approximately 10^8 ohm-cm. They are cut with a 6 mm. cross section and 0.1 mm. thickness along the BM series. Theta equals 42°. Each wafer is electroded with sputtered indium overcoated with vapor deposited gold. A fused silica delay medium is used which is 8 mm. in cross section and 12.7 mm. in length. This medium has its opposed ends mechanically polished flat and perpendicular to the center line thereof. One BM series zinc oxide transducer is adhered to each such end of the delay medium by the use of a high shear strength epoxy resin adhesive. In this bonding operation, heat and pressure are used to adhere the transducers to the fused silica to insure a thin (under 0.1 mm.) epoxy resin layer which is completely cured.

Thereafter, the metallic electrodes of each transducer are connected in succession first to an external signal source and then to a receiving circuit. The transducers are observed to convert the input electrical signal into a thickness shear wave and then back again. The observed delay time is 3.4μ sec. at a center frequency of 15 megahertz using the fused silica delay medium, and is about 4.2μ sec. using the BM series of zinc oxide delay medium.

The bandwidth of each transducer when terminated for perfect power conversion is 4.2% compared to 2.0% for a transducer prepared using a conventional zinc oxide crystal with a crystallographic *a* axis cut. The gain-bandwidth product of the BM series transducer compared to that of the conventional crystallographic *a* axis transducer is about three times larger. The spurious response of the compressional mode is essentially zero for the BM series transducer.

Example 2

The construction here is identical to that shown in FIGURE 5 and above described. Two crystal wafers of DM series single crystal zinc oxide are used as transducers, each one having a resistivity of approximately 10^8 ohm-cm. They are cut with a 6 mm. cross section and 0.1 mm. thickness along the DM series. Theta equals 35°. Each wafer is electroded with sputtered indium overcoated with vapor deposited gold. A fused silica delay medium is used which is 8 mm. in cross section and 12.7 mm. in length. This medium has its opposed ends mechanically polished flat and perpendicular to the center line thereof. One DM series zinc oxide transducer is adhered to each such end of the delay medium by the use of a high shear strength epoxy resin adhesive. In this bonding operation, heat and pressure are used to adhere the transducers to the fused silica to insure a thin (under 0.1 mm.) epoxy resin layer which is completely cured.

Thereafter, the metallic electrodes of each transducer are connected in succession first to an external signal source and then to a receiving circuit. The transducers are observed to convert the input electrical signal into a thickness shear wave and then back again. The observed delay time is 3.4μ sec. at a center frequency of 14.8 megahertz using the fused silica delay medium, and is about 4.2μ sec. using the DM series of zinc oxide delay medium.

The bandwidth of each transducer when terminated for perfect power conversion is 6.1% compared to 2.0% for a transducer prepared using a conventional zinc oxide crystal with a crystallographic *a* axis cut. The gain bandwidth product of the DM series transducer compared to that of the conventional crystallographic *a* axis transducer is about three times larger.

Example 3

The construction here is identical to that shown in FIG. 6 and above described.

A BM series single crystal zinc oxide amplifying medium having a resistivity of approximately 10^4 ohm-cm. is cut with a 6 mm. cross section and 10 mm. length, along the BM series formed such that Theta equals 43°30′. The zinc oxide crystal has its opposed ends mechanically polished flat and perpendicular to the BM series crystal axis. This crystal is electroded as described in Example 1.

Similarly, two BM series single zinc oxide wafers are cut such that theta equals 43°30′ and so as to have a 5 mm. cross section and a .05 mm. thickness, along the BM series axis. Each crystal is mechanically polished and electroded as in Example 1. Each resulting such crystal is then bonded to the electroded ends of above zinc oxide amplifying medium with an epoxy resin using a procedure like that described in Example 1.

The metallic electrodes of each transducer are connected to an external signal source or to a receiving circuit. The amplifying medium electrodes are connected to a drift field power source. The device operates at approximately 30 megahertz.

The bandwidth of this ultrasonic amplifier, when connected for perfect power conversion, is 4.9% compared to 2.0% for the same device operating with a conventional zinc oxide crystal cut on the crystallographic *a* axis. The maximum gain obtained when operated at $\omega=\omega_c\omega_d$ (where ω_c is the dielectric relaxation frequency and ω_d is the diffusion frequency) using the BM series crystal construction is about 60 db, compared to about 28 db for the crystallographic *a* axis device of conventional construction. Hence, using a BM series crystal zinc oxide, one obtains about a 2.5 times increase in bandwidth along with a 30 db increase in gain compared to a conventional crystallographic *a* axis zinc oxide construction.

Example 4

The construction here is identical to that shown in FIG. 6 and above described.

A DM series single crystal zinc oxide amplifying medium having a resistivity of approximately 10^4 ohm-cm. is cut with a 6 mm. cross section and 10 mm. length, along the BM series formed such that theta equals 30°. The zinc oxide crystal has its opposed ends mechanically polished flat and perpendicular to the DM series crystal axis. This crystal is electroded as described in Example 1.

Similarly, two DM series zinc oxide crystal wafers are cut so as to have a theta equal to 33° and so as to have a 5 mm. cross section and a .05 mm. thickness, along the DM series axis. Each crystal is mechanically polished and electroded as in Example 1. Each resulting such crystal is then bonded to the electroded ends of above zinc oxide amplifying medium with an epoxy resin using a procedure like that described in Example 1.

The metallic electrodes of each transducer are connected to an external signal source or to a receiving circuit. The amplifying medium electrodes are connected to a drift field power source. The device operates at approximately 30 megahertz.

The bandwidth of this ultrasonic amplifier, when connected for perfect power conversion, is 6.6 compared to 2.0% for the same device operating with a conventional zinc oxide crystal cut on the crystallographic *a* axis. The maximum gain obtained when operated at $\omega=\omega_c\omega_d$ (where ω_c is the dielectric relaxation frequency and ω_d is the diffusion frequency) using the DM series crystal construction is about 80 db, compared to about 28 db for the crystallographic *a* axis device of conventional construction. Hence, using a DM series crystal zinc oxide, one obtains about a 2.5 times increase in bandwidth along with a 40 db increase in gain compared to a conventional crystallographic *a* axis zinc oxide construction.

Example 5

The construction here is identical to that shown in FIGURE 7 and above described.

A CM single crystal zinc oxide wafer, having a resistivity of approximately 10^8 ohm-cm., is cut with a 6 mm. cross section and a .15 mm. thickness, along the CM series theta equal to 24°. The wafer is mechanically polished and electroded as described in Example 1. This wafer is mounted for resonant, anti-resonant bandwidth measurement on a Q-meter. The bandwidth between the resonant frequency and anti-resonant frequency is one measure of the maximum bandwidth in a crystal filter. Similar measurements are made using a single crystal zinc oxide cut along the crystallographic *c* axis. The bandwidth realized for the CM series crystal is approximately 2.3 times that obtained for the crystallographic *a* axis crystal.

It will be obvious to those skilled in the art that the high transverse electromechanical coupling coefficient of the CM series crystals has many device applications. The devices illustrated in the figures are to be considered illustrative and to be understood as indicating the necessary transmission structures as are well known in the art for the transmission of electromagnetic signals. The foregoing examples are offered as exemplary of the magnitude of possible device designs which depend upon the basic teaching of this invention and are not to be construed as limiting the invention. Various other modifications and embodiments will become apparent to those skilled in the art. However, all such devices, which are characterized in whole or part by the basic phenomenon of the CM series through which this invention had advanced the art are properly considered within the spirit and scope of this invention.

I claim:

1. A piezoelectric device comprising at least one element consisting essentially of

a piezoelectric zinc oxide crystal having wurtzite crystal structure and characterized by being capable of propagating an acoustic transverse wave with an efficiency greater than that obtained by generating such wave along the crystallographic *a* plane, in response to a dynamic electric field applied across said crystal in the direction of acoustic transverse wave generation, said crystal having both

(a) a resistivity between about 0.1 and 10^{12} ohm-cm., and

(b) an axis passing through the crystallographic *c* axis and inclined at an angle theta relative to such crystallographic *c* axis, theta ranging from about 13° to 53°; and

means for making electrode contact with said element on at least one face.

2. The piezoelectric device of claim **1** wherein said crystal is further characterized by having maximum transverse coupling efficiency, said crystal further having a value of theta ranging from about 30° to 38°.

3. The piezoelectric device of claim **2** wherein theta is about 33°.

4. The piezoelectric device of claim **1** wherein said crystal is further characterized by being substantially incapable of concurrently propagating an acoustic compression wave, in response to a dynamic electric field applied across said crystal in the direction of acoustic transverse wave generation, said crystal further having a value of theta ranging from about 38° to 49°.

5. The piezoelectric device of claim **4** wherein theta is about 44°.

6. The device of claim **1** in which the smallest dimension of said element corresponds with the inclined axis at an angle theta relative to said crystallographic *c* axis and in which electrode contact is made on two faces perpendicular to the inclined axis.

7. The device of claim **1** in which the smallest dimension of said element corresponds with the inclined axis at an angle theta relative to said crystallographic *c* axis and in which electrode contact is made to two faces in which the inclined axis lies.

8. The device of claim **1** further comprising

means operatively coupled to said electrode contact making means for propagating an acoustic wave signal.

9. The device of claim **8** further comprising

means operatively coupled to said electrode contact making means for applying an electrical signal to said electrode contact making means to produce an acoustic wave signal in said one element.

10. The device of claim **8** further comprising

control means including a D.C. bias source for establishing a D.C. field across said one element, said field having a magnitude and direction such that the drift velocity of the field carriers in said one element have a velocity component along said axis whereby concurrent application of said D.C. field to said one element concurrently with said acoustic wave signal results in said acoustic wave signal being modified.

11. The device of claim **10** further comprising

means operatively coupled to said control means for adjusting the D.C. bias source to establish an acoustic wave signal gain.

12. The device of claim **1** further comprising

means operatively coupled to said electrode contact making means for applying an electrical signal thereto which includes a component having a frequency which is substantially equal to the mechanical resonant frequency; and

receiving means operatively connected to said electrode contact making means to receive therefrom the acoustical wave signal passed by said one element which is converted by said electrode contact making means into an electrical signal which is formed substantially of the component having a frequency which is substantially equal to the mechanical resonant frequency of said one element.

13. The device of claim **12** further comprising

control means including a D.C. bias source for estab-

lishing a D.C. field across said one element, said field having a magnitude and direction such the drift velocity of the field carriers in said device have a velocity component along said axis, said control means being adapted to influence said acoustical wave signal.

14. The device of claim **13** further comprising

means operatively coupled to said control means for adjusting the D.C. bias source to establish the mechanical resonant frequency of said element.

15. A piezoelectric element adapted for use as a piezoelectric transducer comprising

a zinc oxide crystal capable of propagating an acoustical transverse wave along an axis through the crystallographic *c* axis and inclined at an angle theta ranging from about 13° to 53° and wherein said

crystal has a resistivity between about 0.1 and 10^{12} ohm-cm., said crystal having an efficiency of propagation along said inclined axis greater than that along its crystallographic *a* plane in response to a dynamic electrical field applied across said crystal in the direction of acoustic transverse wave propagation.

References Cited

Gibson, "Electronics Letters," June 1966, p. 213.

ROY LAKE, *Primary Examiner.*

DARWIN R. HOSTETTER, *Assistant Examiner.*

U.S. Cl. X.R.

333—30, 70, 72; 310—9.5

U.S. DEPARTMENT OF COMMERCE

PATENT OFFICE

Washington, D.C. 20231

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,440,550 April 22, 1969

Arthur R. Moore

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 7, line 4, "30°" should read -- 33° --.

Signed and sealed this 14th day of April 1970.

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents