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PIEZOELECTRIC TRANSDUCER

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FIG. 1

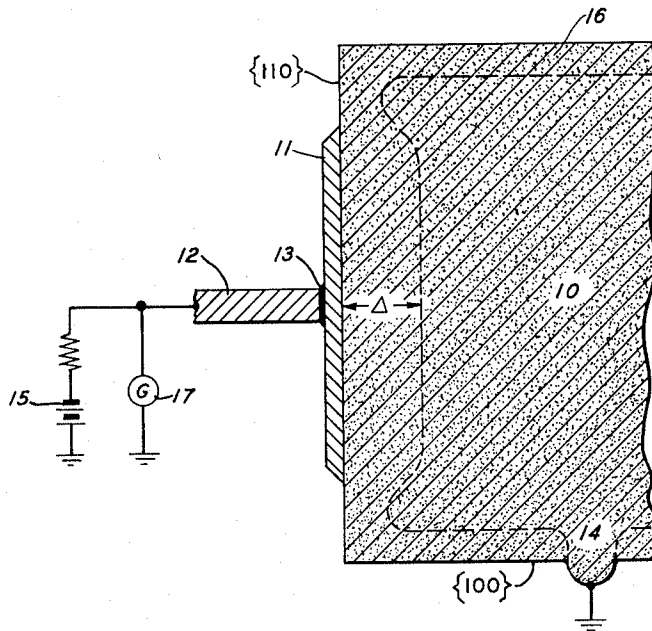
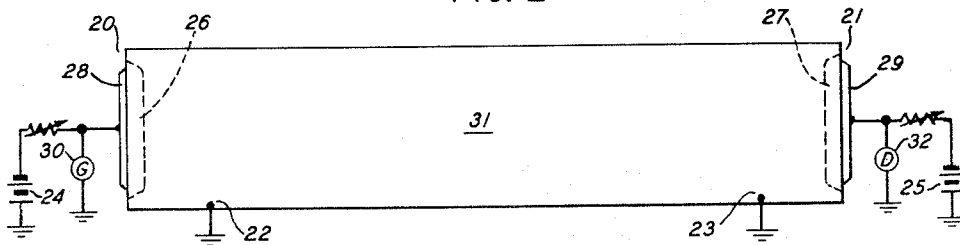


FIG. 2



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## PIEZOELECTRIC TRANSDUCER

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10 Claims. (Cl. 333—30)

This invention relates to piezoelectric transducers. It concerns a novel type of transducer which provides for use at extremely high frequencies. Additionally, the transducers of this invention are easily fabricated and possess a convenient mechanism for varying the frequency of response. The device as described herein finds a wide variety of uses among the more significant of which are variable frequency detectors, variable frequency filters, variable frequency standards, and variable frequency ultrasonic delay lines. Modulators and attenuators can also be operated using the procedures outlined in this invention.

It is well known that the piezoelectric phenomenon appears only in high resistance solids. Consequently, significant piezoelectric effects have not been seen in semiconductors as they are generally too conducting to support the requisite electric field intensity. Some such effects have recently been noted in specially prepared, high resistivity semiconductors such as CdS and ZnO.

According to the present invention, semiconductive materials are employed in a special manner to support an electric field large enough to produce a piezoelectric response. It has been found that in the depletion layer formed at a p-n junction or other non-ohmic contact, the population of the carriers is reduced to a degree such that the material of the layer becomes sufficiently non-conducting to support a piezoelectric field.

A piezoelectric element utilizing such a depletion layer region gives rise to operating advantages heretofore unobtainable in such devices. Of particular consequence is the high frequency of operation provided by a depletion layer piezoelectric device. It is well accepted that electromechanical transducers function most efficiently at a frequency corresponding to their fundamental mode. Prior art transducers using such materials as quartz, KDP, and Rochelle salts, have utilized fundamental modes of from 1 mc. to 60 mc. Crystal resonators having fundamental modes above this range are so delicate and small as to be physically impractical. Consequently, for high frequency transducers the art typically utilizes harmonics of the larger crystals. In this manner frequencies as high as 1000 mc. have been produced. However, the use of harmonics introduces some very extreme difficulties. Proper coupling between the resonating crystal and the surrounding propagating medium requires a high degree of alignment and is quite inefficient. However, transducers which resonate at or near their fundamental mode provide a high degree of electromechanical coupling and are inherently highly efficient.

For the purposes of this invention, the thickness of the depletion layer may be of the order of  $10^{-3}$  cm. to  $10^{-6}$  cm. as measured parallel to a piezoelectric axis of the material. Transducers employing piezoelectric fields across depletion layers of these dimensions may have fundamental modes corresponding to a range approximating 200 mc. to well over 100,000 mc. This is a striking improvement over the high frequency transducers of the prior art.

A further feature which renders the transducers of this invention particularly attractive is the ease of varying the fundamental resonant frequency. The thickness of the depletion layer is directly responsive to the reverse bias applied to the junction. Accordingly, the thickness of the layer, and the attendant fundamental resonant fre-

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quency, is easily varied merely by changing the reverse bias voltage. For example, in one particular class of crystals a 25% decrease in voltage results in a 13% increase in fundamental frequency, the fundamental frequency varying as the inverse of the square root of the voltage.

It is evident to those skilled in the art that the depletion layer in the semiconductor must extend substantially in the direction of a piezoelectric axis of the material. Although preferred, the thickness of the layer is not of necessity required to correspond to a piezoelectric axis as long as a portion of the axis lies in the depletion layer region. That is, it is not essential that the axis be normal to the layer.

The non-ohmic contact is made on the face of the crystal which is here termed a piezoelectric face. The term piezoelectric face as used herein and in the appended claims is intended to define a face which is related to a piezoelectric axis such that a signal introduced in a direction perpendicular to the face will establish a significant piezoelectric field in the crystal. Obviously the preferred piezoelectric faces are substantially perpendicular to a piezoelectric axis; however, as stated above, departures from this optimum orientation can be tolerated while still obtaining the desired piezoelectric effects. Where the depletion layer is formed adjacent a p-n junction which exists in the interior of the semiconductor material, it is apparent that the layer still must extend substantially in the direction of a piezoelectric axis.

A typical device constructed according to the teachings of this invention is shown in the drawings wherein:

FIG. 1 is a front section of a device utilizing a depletion layer to support a piezoelectric field; and

FIG. 2 is an ultrasonic delay line constructed with two depletion layer transducers.

FIG. 1 for convenience is discussed in conjunction with a particular embodiment detailing the construction features of a typical piezoelectric transducer according to the invention.

A cube of semiconductive material 10 approximately 6 mm. in dimension is used to support the piezoelectric field. In this embodiment the material 10 is n-type GaAs doped with  $5 \times 10^{15}$  impurity atoms/cc. This doping level appears low; however, due to the high mobility of electron carriers the resistivity of this material is less than 0.1 ohm.-cm. The cube is polished optically flat on the (110) face to insure a coherent wave front. A gold film 11 is then evaporated on these faces to a depth of approximately  $5 \times 10^{-6}$  cm. Gold on GaAs provides the requisite non-ohmic contact. Contact is made to the gold layer with a copper wire 12 using an indium bond 13. An ohmic contact 14 is provided on the (100) face.

A reverse bias 15 of 10 volts (D.C.) applied across gold electrode 11 on the (110) face and ohmic contact 14 results in a depletion layer 16 approximately  $1.6 \times 10^{-4}$  cm. in thickness. A signal imposed across this layer by high frequency A.C. generator 17 results in an acoustical vibration in the semiconductor which has a fundamental resonant mode corresponding to 1000 mc.

The thickness of the depletion layer can be calculated according to the equation:

$$\Delta = \left( \frac{2\epsilon V_t}{Nq} \right)^{1/2} \quad (1)$$

where  $\Delta$  is the thickness of the depletion layer,  $\epsilon$  is the permittivity,  $V_t$  is the reverse bias,  $N$  is the number of ionized impurities per unit volume and  $q$  is the electronic charge all in compatible units. For a more thorough presentation of this basic equation, see "An Introduction to Junction Transistor Theory," by Middlebrook, J. Wiley, pages 160-163. For the example given,  $\epsilon$ , the permittivity is equal to  $K_1\epsilon_0$ , where  $K_1$  the dielectric constant is

11 and  $\epsilon_v$ , the permittivity of a vacuum is  $8.85 \times 10^{-12}$  farads/m.;  $V_t$ , the reverse bias is 10 volts,  $N$  is  $5 \times 10^{21}$  impurities/m.<sup>3</sup> and  $q$  is  $1.6 \times 10^{-19}$  coulombs. Inserting these values in Equation 1 results in a  $\Delta$  of  $1.6 \times 10^{-6}$  meters.

To obtain the fundamental frequency of a depletion layer having this thickness use is made of equation:

$$f = v/\lambda \quad (2)$$

where  $\lambda$  is the wavelength corresponding to twice the thickness of the depletion layer. The velocity of sound,  $v$ , through this medium is obtained from:

$$v = \sqrt{\frac{c}{\rho}} \quad (3)$$

where  $\rho$  is the density of the material and  $c$  is the elastic constant in compatible units. The elastic constant is dependent on the crystallographic orientation. For GaAs, for instance, in the (110) direction, for piezoelectrically excited shear waves  $c = c_{44} = 5.94 \times 10^{11}$  dynes/cm.<sup>2</sup>. In the (111) direction for this material, for longitudinal waves

$$c = \frac{1}{3}(c_{11} + 2c_{44} + 4c_{12}) = 1.509 \times 10^{11} \text{ dynes/cm.}^2$$

For a more thorough treatise concerning these values see Bateman, McSkimin and Whelan, "Journal of Applied Physics" 30, page 544, April 1958. The density  $\rho$  of GaAs is 5.31 gm./cm.<sup>3</sup>. Using these values in Equation 3:

$$v = \sqrt{\frac{5.94 \times 10^{11} \text{ dynes/cm.}^2}{5.31 \text{ gm./cm.}^3}} \quad (110)$$

$$v = 3.20 \times 10^5 \text{ cm./sec.}$$

Using this value of  $v$  and the value of  $\Delta$  obtained from Equation 1 and recognizing that  $\lambda = 2\Delta$ , Equation 2 then provides a fundamental resonant frequency  $f$  of 1000 mc.

The frequency of resonance may be easily varied merely by adjusting the reverse bias voltage. As is seen from Equations 1 and 2 the resonant frequency varies as the inverse of the square root of the reverse bias voltage. In the example given a reduction of the D.C. voltage to 9 volts results in a fundamental resonant frequency of 1054 mc.

This variable frequency mechanism allows for extremely useful device applications. Since prior art ultrasonic transducers depended essentially on the physical size of the resonant crystal, variation of the resonant frequency was effectively available only through a change of crystals. The present invention provides highly effective variation of the fundamental resonant frequency merely through adjustment of the bias voltage. Such an adjustment mechanism is highly useful in devices such as variable pass filters, variable frequency oscillators, variable frequency detectors, and variable frequency ultrasonic delay lines. The latter use is particularly significant. One delay line installation with minor adjustment in reverse bias can accommodate signals over an extremely wide bandwidth. This has been impossible to obtain with prior art delay lines.

A typical ultrasonic delay line with variable frequency transducers is shown in FIG. 2. Each transducer 20 and 21 is essentially the same as that shown in FIG. 1 and is attached to an appropriate face, for instance, using GaAs, the (111) or (110) faces. The delay medium 31 is any well-known acoustical delay material suitable for these frequencies or may conveniently be the semiconductor material itself. Ohmic contacts 22 and 23 are provided as shown. Each end of the delay line is then reverse-biased by D.C. sources 24 and 25 so that depletion layers 26 and 27 appear adjacent each non-ohmic contact 28 and 29. The signal is injected at one end by high frequency A.C. source 30 which may be the input from a signal circuit. Transducer 20 creates an acoustical signal which

is transmitted through delay medium 31 to the other transducer 21 where it is converted to an electrical pulse signal and detected at high frequency detector 32.

The contacts 14, 22 and 23 are referred to as ohmic contacts; however, it will be apparent to those skilled in the art that non-ohmic contacts may be used if their resistance is substantially less than the resistance of the non-ohmic contacts 11, 28 and 29 each resistance measured in a direction away from the depletion layer. For the purpose of this invention in obtaining a proper operation of the device, the resistance of the contacts 14, 22 and 23 for a forward current should preferably be less than half of the resistance of the non-ohmic contact to reverse currents. In considering a p-n junction device where the junction is formed in the interior portion rather than adjacent an exterior contact as shown in FIGURE 1, this limit requires that the contact have a resistance to forward currents of less than half the resistance of the said p-n junction to reverse currents.

The semiconductor materials useful in the devices of this invention are those in which a depletion layer of the desired thickness can be generated while still retaining a high mobility and high conductivity. The III-V and II-VI class semiconductors provide these desiderata. Preferred materials are GaAs, GaP, GaSb, BP, AlP, AlAs, AlSb, CdS, CdO, ZnS, ZnO and at low temperatures, InSb.

One of the vitalizing requisites of this invention is a piezoelectric body capable of supporting a depletion layer in the manner previously prescribed. In this connection it is generally immaterial how or by what means the required depletion layer is formed. Thus the device will be effective whether the depletion layer is formed adjacent an exterior non-ohmic contact or in the interior of the semiconductor body at a conventional p-n junction. The essential behavior of the junction in order to form a depletion layer is that it be rectifying or non-ohmic. Accordingly, here and in the appended claims, the term p-n junction is intended to define any junction at which a depletion layer can be produced.

The frequency variability feature of the transducers of this invention coupled with their high frequency performance provides a significant contribution to the art. Various other uses and modifications available through the versatile and superior characteristics of this invention will become apparent to those skilled in the art and are considered as appropriately within the scope of this invention.

What is claimed is:

1. A piezoelectric transducer comprising a piezoelectric semiconductor material, a D.C. source connected to a piezoelectric face of said semiconductor material, a p-n junction in the semiconductor material and a depletion layer accompanying said p-n junction, said depletion layer extending substantially in the direction of a piezoelectric axis of said material and having a thickness as measured in a direction parallel to a piezoelectric axis in the range of  $10^{-3}$  cm. to  $10^{-6}$  cm., an electrical lead attached to a piezoelectric face of said semiconductor material and adapted to carry a high frequency signal and an additional ground contact on an adjoining face of said semiconductor, said contact having a resistance to forward currents of less than half the resistance of the said p-n junction to reverse currents.
2. A piezoelectric transducer comprising a piezoelectric semiconductor material, a D.C. source connected to a piezoelectric face of said semiconductor material through a non-ohmic contact whereby a depletion layer exists in said semiconductor, said layer having a thickness within the range  $10^{-3}$  cm. to  $10^{-6}$  cm., a high frequency A.C. generator connected to said face and a contact on an adjoining face of said semiconductor and adjacent to the said piezoelectric face, said contact having a resistance to forward currents which is less than half the resistance of the said non-ohmic contact to reverse currents.

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3. A piezoelectric transducer comprising a piezoelectric semiconductor material, a D.C. source connected to a piezoelectric face of said semiconductor material through a non-ohmic contact whereby a depletion layer exists in said semiconductor, said layer having a thickness within the range  $10^{-3}$  cm. to  $10^{-6}$  cm., a high frequency A.C. detector connected to said face and an ohmic contact on an adjoining face of said semiconductor and adjacent the said piezoelectric face.

4. The device of claim 1 wherein the semiconductor material is GaAs.

5. A variable frequency ultrasonic delay line comprising an acoustical transmission medium, and a pair of piezoelectric transducers attached to opposing ends of said medium, said transducers each comprising a semiconductor material a D.C. source connected to a piezoelectric face of semiconductor material through a non-ohmic contact whereby a depletion layer exists in said semiconductor, said layer having a thickness within the range  $10^{-3}$  cm. to  $10^{-6}$  cm. and an ohmic or low resistance contact on an adjoining face of said semiconductor adjacent to said piezoelectric face said delay line additionally including a high frequency A.C. source connected to said piezoelectric face of a first of said pair of transducers and a high frequency A.C. signal detector connected to said piezoelectric face of said second transducer.

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6. The device of claim 5 wherein the semiconductor material is GaAs.

7. The device of claim 1 wherein the p-n junction is formed in the interior body of the semiconductor material.

8. The device of claim 1 wherein the p-n junction is formed adjacent a non-ohmic contact.

9. The device of claim 1 wherein the D.C. source is adjustable.

10. The device of claim 5 wherein the D.C. source is adjustable.

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