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Whitney et al.

[11] **3,714,609**

[45] **Jan. 30, 1973**

[54] **MICROWAVE ULTRASONIC DELAY LINE**

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[22] Filed: **July 31, 1970**

[21] Appl. No.: **60,151**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 656,273, July 26, 1967, abandoned.

[52] **U.S. Cl.** .....**333/30 R,** 330/5.5

[51] **Int. Cl.** **H03h 7/30,** H03h 9/30

[58] **Field of Search** 333/30, 71; 330/5, 5.5, 31; 310/8.2, 9.4; 317/235; 331/107

[56] **References Cited**

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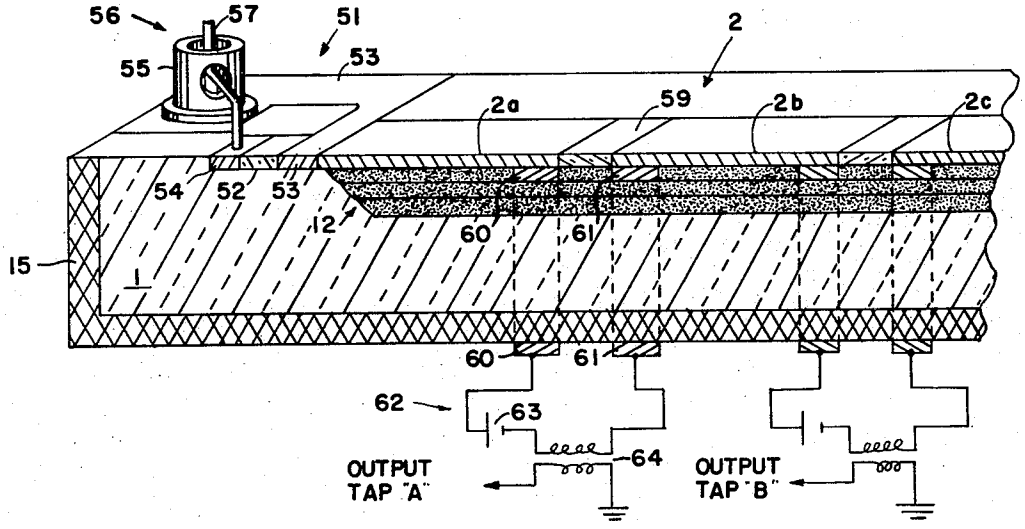
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[57] **ABSTRACT**

An ultrasonic delay line for use at microwave frequencies is provided in a thin epitaxial strip of ultrasonic wave conducting material laid down on a substrate body. An input transducer launches ultrasonic waves into the epitaxial strip at one end and an output transducer detects the ultrasonic waves at the other end of the strip. The major surfaces of the epitaxial strip are preferably adjacent a medium such that the interface therewith is highly reflective to the ultrasonic waves and the thickness of the epitaxial strip is precisely determined when it is formed so that the thickness is of the same order of magnitude as the inflection thickness for the material at an ultrasonic frequency in the microwave range.

9 Claims, 13 Drawing Figures



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4 Sheets-Sheet 1

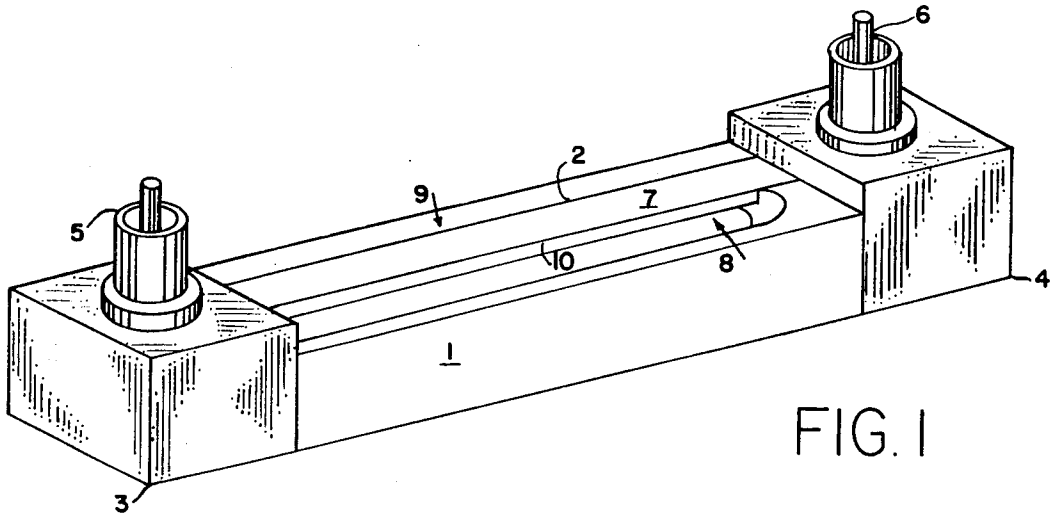


FIG. 1

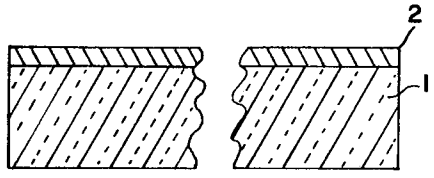


FIG. 2

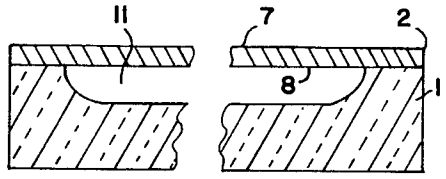


FIG. 3

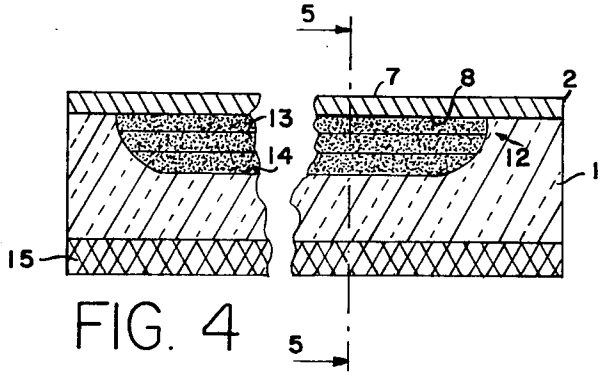


FIG. 4

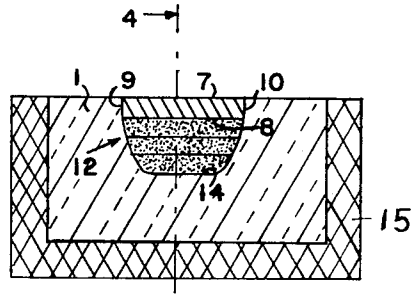


FIG. 5

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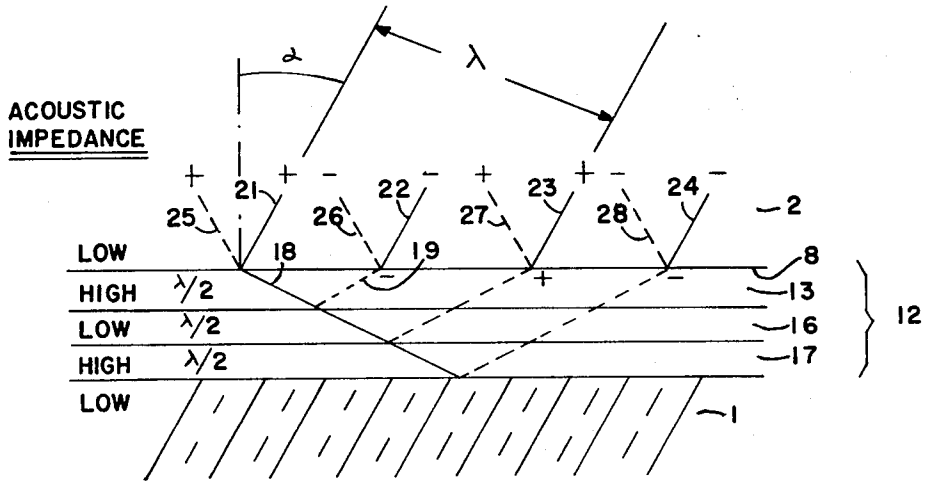


FIG. 6

FIG. 7

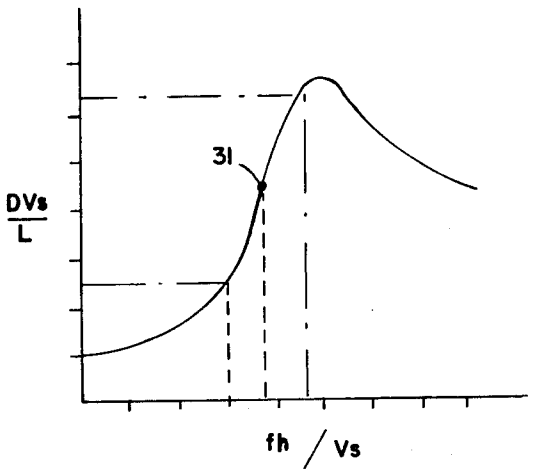
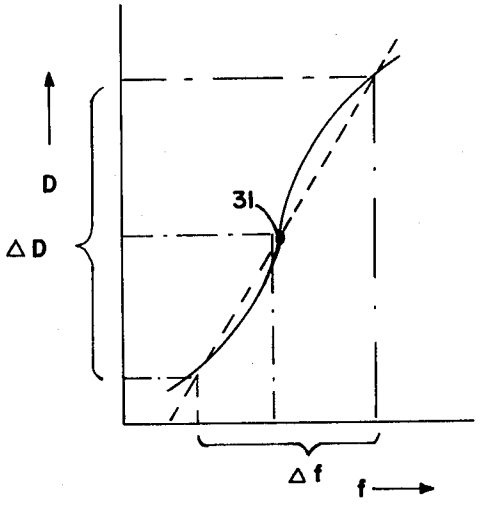


FIG. 8



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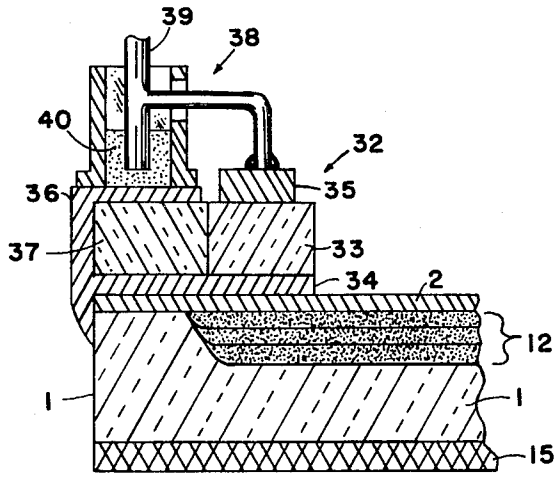


FIG. 9

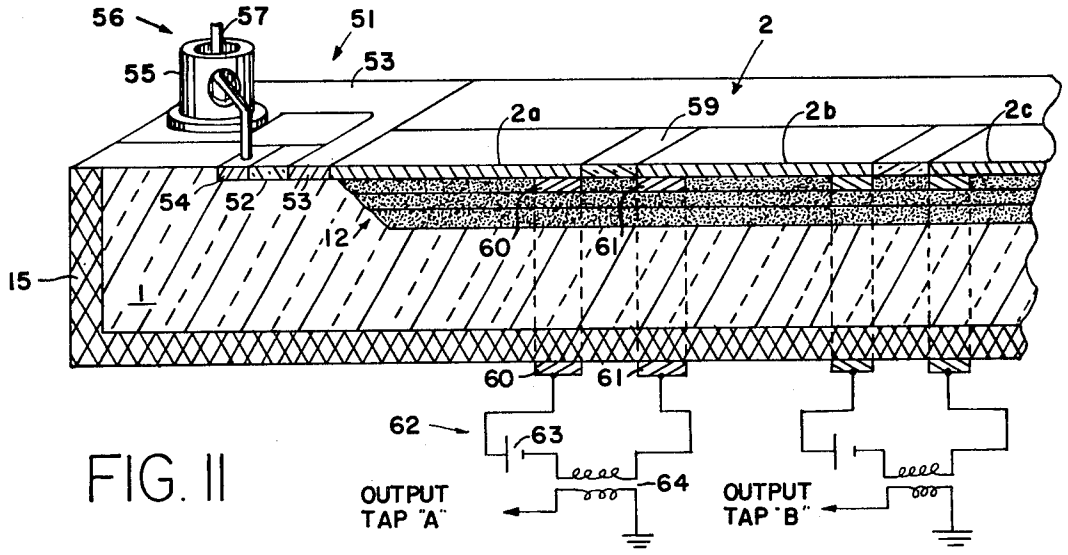


FIG. II

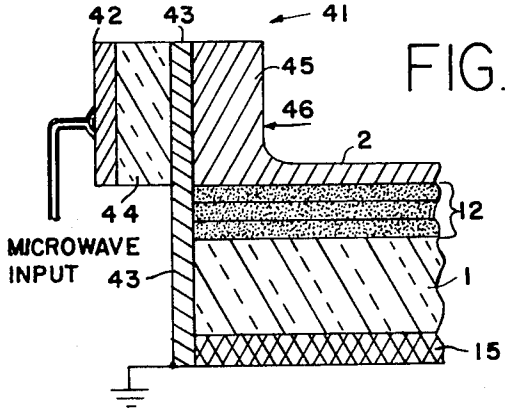


FIG. 10

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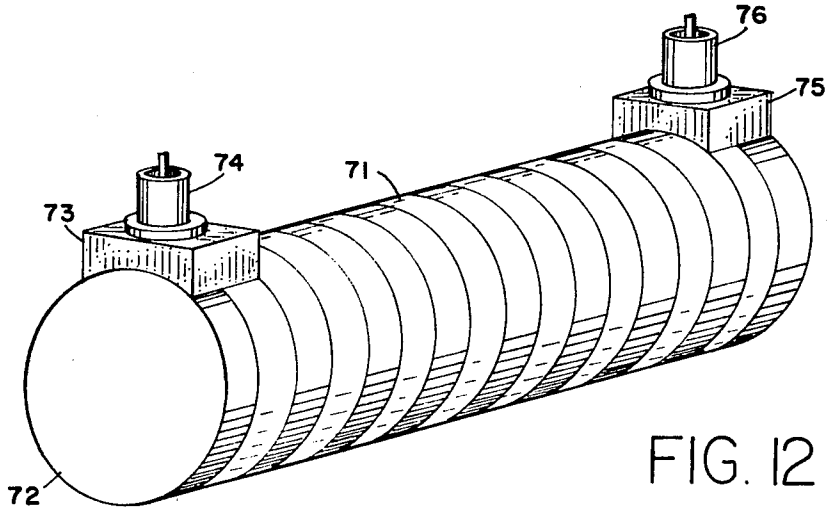


FIG. 12

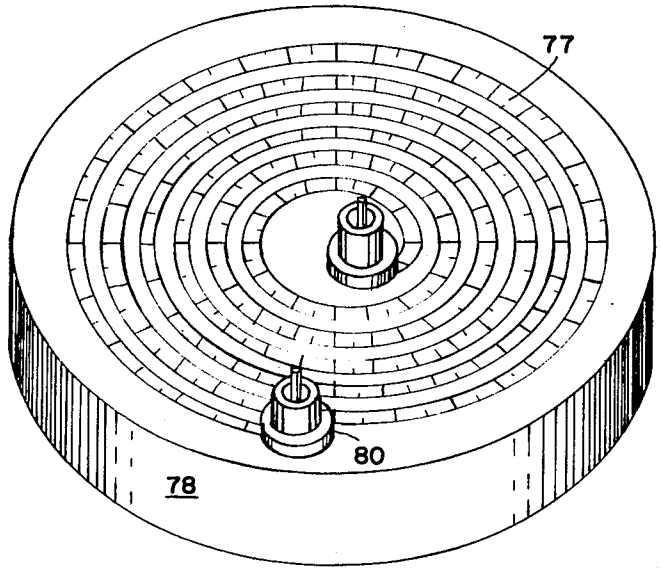


FIG. 13

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MICROWAVE ULTRASONIC DELAY LINE

This application is a continuation-in-part of our co-pending application Ser. No. 656,273 now abandoned.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

This invention relates to ultrasonic delay lines and more particularly to strip type dispersive delay lines wherein ultrasonic material waves are launched into one part of the strip and are detected at another part a predetermined delay interval later.

Heretofore, ultrasonic delay lines have been formed of wires and of strips. The ultrasonic waves are launched into one end of the wire or strip by means of a transducer and are detected at another part by another transducer. The delay is produced by the relatively slow velocity of the ultrasonic wave through the medium of the strip as compared with the velocity of electromagnetic waves in a conductor. In the strip type dispersive delay lines, the geometry of the strip, the material of the strip, and the mode of the ultrasonic wave launched into the strip by the transducer are such that the time delay varies with the frequency. In non-dispersive strips, on the other hand, the time delay is substantially constant over the frequency band of use.

In the frequency range 1 to 10 Mhz, dispersive strip delay lines made of aluminum alloy have been used. For example, a strip 56 inches long, 1½ inches wide and 0.086 inches thick produces a 633 microsecond delay at the center frequency of one Megahertz and a 200 microsecond delay change over a 100 KH_z bandwidth. Dispersion is approximately linear about the inflection point on the dispersion curve (frequency versus delay) over the bandwidth. Efforts have been made to provide dispersive ultrasonic delay lines for operation at higher frequencies and with wider bandwidths. For example, fused quartz strip lines on the order of about 0.005 inches thick have been used at 30 Megahertz but mechanical difficulties of fabricating the quartz strip have not been overcome.

OBJECTS AND SUMMARY OF THE INVENTION

It is one object of the present invention to provide an ultrasonic delay line for use at frequencies higher than practicable with ultrasonic delay lines in the past.

It is another object of the present invention to provide an ultrasonic delay line having substantially linear dispersion over a wider bandwidth than obtained heretofore.

It is another object of the present invention to provide an ultrasonic delay line having tolerable insertion losses for operation in the microwave frequency range.

It is another object to provide a solid state ultrasonic delay line.

In accordance with principle features of embodiments of the present invention, a dispersive strip type ultrasonic delay line is provided in an epitaxial strip of ultrasonic wave conducting material on a substrate body. The strip is laid down on the substrate employing well-known epitaxial layer growth techniques and is of uniform thickness and a few microns thick. The thickness is predetermined so that at the selected operating frequency, for example, 1,000 Mhz, operation is around the lower inflection point in the delay versus frequency curve of the first longitudinal mode.

For a specific material, this inflection point will occur at a fixed frequency times thickness product. For example, by extrapolation at 1,000 Mhz the inflection thickness for a strip of 5052H32 aluminum would be about 2 microns. Hence, a strip 2 microns thick by 1.40 inches long would produce a delay change of 5 microseconds over a 100 Mhz bandwidth. If the delay linearity desired is 0.5 percent and the bandwidth is 10 percent, then this 2 micron aluminum strip would serve in a system having compression ratio of 500 to 1.

The major surfaces of the epitaxial strip for conducting the ultrasonic waves must form interfaces with the surrounding medium which is highly reflective to the ultrasonic waves, whereas reflections from the minor surfaces of the epitaxial strip are to be avoided. Optimum reflection is obtained when the surrounding medium adjacent the major surfaces is a vacuum and the medium adjacent the minor surfaces along the edge of the epitaxial strip is highly absorbent and reflects substantially none of the ultrasonic waves. If it is inconvenient to provide a vacuum adjacent the major surfaces of the epitaxial strip, then a gaseous environment may serve just as well, because most gases have an extremely low acoustic characteristic impedance and will reflect close to 100 percent of the ultrasonic acoustic energy conducted within the strip which is incident upon the interface at the major surface.

In the event that it is inconvenient to employ either a vacuum or a gas adjacent one or both of the major surfaces of the epitaxial strip, then solid materials can be employed consisting of a plurality of thin film layers one upon another immediately adjacent either one or both of the major surfaces of the epitaxial strip. The plurality of layers of thin film are of selected thickness and selected acoustic characteristic impedance so that they provide in effect a highly reflective surface at the interface with the epitaxial delay strip. For example, if the acoustic wave path across each thin film is an integral number of half wavelengths of the ultrasonic wave and if the thin films are alternately of relatively high and relatively low acoustic impedance, then an effective interface will be produced at the major surface of the epitaxial strip delay line adjacent these thin films which is substantially highly reflective to the ultrasonic waves. A number of embodiments of the present invention illustrate the use of a plurality of such thin films adjacent one major surface of the epitaxial strip delay line and with vacuum or gas environment adjacent the other major surface to provide a compact rugged structure for use in the microwave frequency range.

Embodiments of the present invention described herein include such an epitaxial strip delay line supported by a substrate body and having a piezoelectric type transducer at each end thereof, one for launching ultrasonic waves into the epitaxial strip and the other for converting the ultrasonic waves into a high frequency electrical signal. The transducers consist of, for example, semiconductors which exhibit significant piezoelectric effects such as CdS, and which preferably match the acoustic characteristic impedance of the epitaxial strip so that the ultrasonic waves are launched from the transducer into the strip with negligible reflection at the interface therebetween. The transducer material is preferably selected so that it has about the same acoustic characteristic impedance as the epitaxial

strip and if this is inconvenient then the transducer may be comprised of a plurality of layers of materials of selected acoustic characteristic impedance between the transducer piezoelectric material and the epitaxial strip. These layers serve to match the characteristic impedances between the two, and thereby, produce minimum reflection. Multi-layer transducers of this sort are described in an article entitled "Multi-Layer Thin Film Piezoelectric Transducers" by John DeKlerk on page 99 of IEEE Transactions on Sonics and Ultrasonics, Volume SU13, No. 3, August 1966.

Other objects and features of the present invention will be apparent from the following specific description taken in conjunction with the appended figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a three-quarter view of the epitaxial strip delay line supported by a substrate body and with transducers at each end for coupling to microwave transmission lines;

FIGS. 2 and 3 are sectional views showing the epitaxial strip delay line and substrate to illustrate steps in making the device;

FIGS. 4 and 5 are longitudinal and transverse sectional views of the epitaxial strip delay line and substrate showing a plurality of layers of thin film adjacent one major surface of the strip for reflecting ultrasonic waves transmitted through the major surface;

FIG 6 is a model illustrating reflections from a number of thin layers into the delay line strip in phase coincidence with waves therein;

FIG. 7 is a plot of dimensionless parameters representing delay and frequency for a typical dispersive ultrasonic strip delay line;

FIG. 8 is a plot of delay versus frequency for the same typical dispersive ultrasonic strip delay line;

FIGS. 9, 10 and 11 are sectional views taken longitudinally through the epitaxial strip delay line and substrate to illustrate various transducer configurations for converting high frequency electrical waves into ultrasonic acoustic waves and for converting the ultrasonic acoustic waves into high frequency electric waves;

FIG. 12 is a three-quarter view of the epitaxial strip delay line and transducers supported on a rod shaped substrate so that the strip defines a helix along which the ultrasonic waves are conducted; and

FIG. 13 illustrates the epitaxial strip delay line and transducers on a substantially flat substrate body, the strip defining a spiral path along which the ultrasonic waves are conducted.

DESCRIPTION OF PREFERRED EMBODIMENT

FIG. 1 illustrates fundamental features of the present invention and the principle parts thereof. These include an elongated substrate body 1 which supports an epitaxial layer 2 of selected single unitary crystalline material forming the strip delay line and which couples with the input transducer 3 at one end and the output transducer 4 at the other end. These transducers may each be equipped with coaxial transmission line couplings such as 5 and 6 which connect with an input transmission line and an output transmission line, respectively. The major surfaces 7 and 8 of the epitaxial strip delay line are preferably immediately adjacent an environment which forms an interface with these surfaces such that the ultrasonic waves conducted by the strip reflect from the interface and a negligible amount of ultrasonic wave energy is transmitted through the interface and absorbed by the environment. Along at least one of the minor surfaces 9 and 10 of the strip, the substrate material 1 may abut the strip so that acoustic energy transmitted through these minor surfaces is absorbed by the substrate material. It is preferred that such absorption occur along a substantial portion of the minor surface of the strip to avoid interference phenomena due to multiple reflections between the minor surfaces. It is sufficient if such absorption occurs along at least one of the minor surfaces, preferably along the entire length of the strip and for this reason the minor surface 9, concealed from view in FIG. 1, preferably abuts the substrate material 1 along its entire length, whereas the minor surface 10 may form an interface with the non-reflective environment which surrounds the major surfaces.

The most highly reflective interface that can be obtained at the surface of an acoustic wave conducting material is an interface with a vacuum. In order to provide such a vacuum interface at each of the major surfaces of the epitaxial strip in FIG. 1, the epitaxial strip is first formed on the substrate body 1 employing well-known vapor or liquid phase epitaxial growth techniques to lay down the epitaxial strip 2 a few microns thick on the substantially thicker, sturdier substrate body 1. This is shown in the longitudinal cross section of the strip and substrate in FIG. 2. Next, a portion of the substrate body immediately adjacent the lower major surface 8 of the strip is removed leaving a hollow 11 in the substrate which the strip in the form of an epitaxial membrane bridges. This can be done employing well-known photo-etch techniques, whereby the substrate material is dissolved to a predetermined depth. Or, a portion on the surface of the substrate upon which the epitaxial strip is formed may be of a material of substantially lower melting temperature than the substrate body proper or the epitaxial strip and so the composite may be heated to melt and drain off this material leaving the epitaxial strip or membrance with two major surfaces 7 and 8 exposed along substantial portions thereof to an environment which may be a vacuum environment or a gaseous environment.

As mentioned above, at least one of the minor surfaces 9 or 10 of the strip preferably abuts an acoustic wave absorbing material for attenuating undesirable acoustic wave modes in the strip. This can be accomplished by growing the epitaxial strip 2 on the substrate body 1 as shown in FIG. 2 and then performing the photo-etch process along only one minor surface 10 of the strip so that the substrate material is removed along the lower major surface 8 up to and just short of the other minor surface 9 leaving minor surface 9 in contact with the substrate material.

The high reflection at a solid to gas interface can also be obtained at an interface between solid materials even though the characteristic acoustic impedance of the solid materials are of the same order of magnitude. A plurality of layers of thin films of solid material of predetermined thickness and of material of predetermined acoustic characteristic impedance adjacent solid wave conducting material, will produce a high reflec-

tion to those waves at the interface. The phenomena is somewhat analogous to the well-known optical dielectric mirror. The optical dielectric mirror is formed by laying down a plurality of dielectric films on a transparent light conducting medium. These optical films are of alternately high and low refractive index and preferably one-quarter optical wavelength thickness and can be designed to reflect over 90% of the optical radiation incident thereon. An analogous acoustic wave reflection structure is described in U.S. Pat. No. 3,422,371 entitled "Thin Film Piezoelectric Oscillator" by Poirier and Newkirk. An epitaxial strip delay line structure employing a plurality of thin films adjacent one major surface of the strip, all carried on the substrate body is illustrated in the longitudinal and transverse section views shown in FIGS. 4 and 5, respectively.

As shown in FIG. 4, a plurality of layers 12 of thin films of selected material are laid down on a portion of the upper surface of the substrate body 1. The epitaxial strip delay line 2 is formed on these thin film layers so that a substantial portion of the lower major surface 8 of the strip forms an interface with the uppermost thin film layer 13. The thin films and the epitaxial strip are preferably formed in a cavity 14 in the substrate body 1 so that the minor surfaces 9 and 10 of the strip abut the substrate body while the other major surface 7 forms an interface with the surrounding environment which may be a vacuum or gas. The sides and bottom of the substrate body 1 are preferably clad in an acoustic wave absorbing material 15 so that acoustic energy transmitted through the minor surfaces of the delay line strip or through the layers of thin film are absorbed. For this purpose, absorbing material 15 is provided along the sides and bottom of the substrate body 1.

The reflections of the high frequency acoustic waves from the layers of thin film 12 are illustrated in the model diagram of FIG. 6. This diagram shows the thin film layers 12 in cross section between the epitaxial strip delay line 2 and the substrate body 1. Three such thin film layers 13, 16 and 17 are shown. In operation, the incident high frequency acoustic waves represented by the positive and negative phase wave front positions 21 to 24 shown as heavy solid lines are incident upon the thin film 13 immediately adjacent the epitaxial strip. The angle of incidence of these waves is denoted α and the angle of reflection of these same waves is also α. The corresponding reflective wave front positions at this interface are represented by the heavy broken line. These incident and reflected wave front positions are all denoted positive or negative phase and represent conditions at a given instant of time. The distance between the successive incident positive wave fronts is a wavelength λ of the high frequency acoustic energy in the strip 2 and the angle α is the angle of incidence of the dominant longitudinal mode of such waves conducted in the strip 2.

The first thin film layer 13 adjacent the epitaxial strip 2 is composed of a material of substantially higher acoustic characteristic impedance than the material composing in the strip and so the reflected acoustic wave front at positions 25 to 28 are in the same phase as the associated incident wave fronts. A portion of the incident wave front energy is transmitted through the layer 13 along the path represented by the light solid line 18 and this portion reflects from the interface between the thin film layer 13 and layer 16 immediately below as indicated by the light broken line 19. The layer 16 is composed of a material of relatively low acoustic characteristic impedance and so the wave incident at the interface between films 13 and 16, upon reflection, experiences a phase reversal. If the thickness of the layer 13 is such that the path of the incident wave through the layer to the reflecting interface between the layers 13 and 16, and from that interface back to the interface 8, is an even number of one-half wavelengths of the acoustic wave to a point along said interface which the same incident wave front strikes an even number of half cycles from the original point of incidence, then the portion which reflects from the interface between films 13 and 16 will re-enter the epitaxial strip in phase coincidence with a reflected wavefront at 26. Thus, it will reinforce the wavefront at 26.

By a similar action, a portion of the wavefront incident on the interface between films 13 and 16 will be transmitted through film 16 to the interface between that film and the next film 17. Since film 17 is composed of material of relatively high acoustic characteristic impedance, the reflection at the interface between films 16 and 17 will not experience a phase reversal and will be returned to the epitaxial strip 2 to reinforce the reflected wave front at position 27.

The interface between film 17 and the substrate also produces a reflection and since the substrate is composed on a material of relatively lower acoustic characteristic impedance, this reflection will experience a phase reversal and the reflection will return to the epitaxial strip to reinforce the reflected wave front position 28 therein. Thus, the plurality of thin films 12 produce a plurality of reflecting surface for the incident high frequency acoustical wave energy such that reflected waves return to the epitaxial strip delay line 2 to reinforce reflected waves at the interface of the strip with the layers of thin films and so this interface behaves just as a near perfect reflector of the incident acoustic waves of a given wavelength λ at a given angle of incidence α.

The model as shown in FIG. 6 is simplified for the sake of brevity and presumes the velocity of the acoustic wave in all the materials shown to be the same. Obviously, the number of layers of thin film can be far greater than shown and the number of layers required will depend upon the relative magnitudes of the acoustic characteristic impedance of the materials. In this model the thin film layer 13 is composed of a material of substantially higher acoustic characteristic impedance than the material composing the epitaxial strip 2, and so there is no phase reversal of reflected wavefronts at this interface. Other models can be envisioned wherein the first layer 13 is of lower acoustic characteristic impedance than the strip 2 and the subsequent layers 16 and 17 are of relatively high and low impedance respectively. In that case, the rule is the same as given above. The incident and reflected wave path through each film is preferably an even number of half wavelengths of the acoustic wave and each path returns to the interface at surface 8 at a point along said surface which is an even number of half cycles from the original point of incidence. It should be quite clear that

the model shown in FIG. 6 is but one combination of thin film layers adjacent a major surface of the epitaxial strip delay line for producing substantial reflection at the major surface while at the same time providing solid support for the strip. The material selected for the films 13, 16 and 17 and the substrate 1 must be such that the model structure as shown in FIG. 6 can be constructed and must be such that the individual films can be formed of very precise thickness in terms of fractions of a wavelength of the high frequency acoustic waves. In addition, the film 13 adjacent the epitaxial strip must be such that the epitaxial layer which comprises the strip can be grown thereon. Various combinations of materials that can be employed to form the epitaxial strip delay line 2, the thin films 13, 16 and 17 and the substrate body 1 such as:

Epitaxial Strip 2	Al_2O_3
Thin Film 13	W
Thin Film 16	Al
Thin Film 17	Au
Substrate Body 1	Si

The performance of the epitaxial strip delay line is illustrated by the curves plotted in FIGS. 7 and 8. FIG. 7 is a plot of the dimensionless delay parameter DV*s*/L versus the dimensionless frequency parameter *fh*/V*s* for the first longitudinal acoustic wave mode in a selected epitaxial strip material. The dimensionless delay parameter plotted on the ordinate in FIG. 7 is the product of the free space sheer velocity V_s of the acoustic wave in the selected material times the delay D per unit length L of the wave in the material. The dimensionless frequency parameter plotted along the abscissa in FIG. 7 is the product of frequency, *f*, times the strip thickness, *h*, divided by the free space sheer wave velocity V_s. On the curve in FIG. 7, the inflection point of the first longitudinal mode is denoted as point 31 and is the preferred point of operation, because the dispersion on each side of this point is substantially linear over the greatest range of frequency and delays. The degree of this linearity is illustrated by the plot in FIG. 8 of delay D versus frequency *f* about the inflection point 31. The broken line in FIG. 8 represents the linear dispersion desired and the solid line represents the actual dispersion characteristics of the line about the inflection point. If, for example, the epitaxial strip 2 is of aluminum and deviation of the actual curve from the desired linear dispersion characteristic is limited to 0.5 percent and the frequency band of operation is centered at 1 Gigahertz, then the bandwidth of operation can be 10 percent and the compression ratio will be over 500 to 1 for a strip 2 microns thick by about one-half inch wide by 1.40 inches long.

The insertion loss in the aluminum strip delay line two microns thick is prohibitively high and so for many applications it is preferred to employ material which has inherently lower insertion loss than the aluminum. Materials which have utility in the practice of the present invention must possess a center of inversion symmetry which excludes any piezoelectric properties and must have a crystallographic plane which exactly matches that of the available transducers. Materials which have been found to have application in the invention include sapphire (Al_2O_3), rutile (TiO_2), spinel ($MgAl_2O_4$, zirconium silicate ($ZrSiO_4$) and zirconate (ZrO_2). Sapphire, for example, in an epitaxial strip of 2 microns thickness exhibits performance characteristics substantially similar to aluminum but has far less insertion loss to the high frequency acoustic waves.

Various forms of input and output transducers and transducers for tapping signals along the epitaxial strip delay line are shown in FIGS. 9 to 11. These figures show the embodiment wherein one major surface of the epitaxial strip is contiguous with a stack of thin films of selected materials and thicknesses so that acoustic energy reflects internally within the strip at the interface of this major surface with the thin films just as already described. The figures each show a cross section taken longitudinally through the center of the epitaxial strip and substrate. The cross section in FIGS. 9 and 10 also cuts through the center of the transducer which may be as wide as the strip.

In FIG. 9, the piezoelectric transducer 32 is a thin film transducer and is preferably acoustically matched to the epitaxial strip delay line 2 against which it abuts. The transducer 32 may be a single layer type or multilayer type, whichever is required to provide an acoustic impedance match, and consists of a film 33 of piezoelectric semiconductor material such as CdS sandwiched between two thin film layers 34 and 35 of electrically conductive material such as gold. The lower conductive layer 34 is contiguous with the epitaxial strip delay line 2. This lower film 34 connects with additional film 36 partially encasing a dielectric support block 37 onto which is mounted a coaxial transmission line connector 38. The center conductor 39 of the transmission line connector connects to the upper conductive film 35 on the piezoelectric semiconductor material. The coaxial connector may include a load 40 for absorbing high frequency electrical energy to reduce reflections from the connector to the transmission line to which it connects.

In operation, the transducer in FIG. 9 is energized by a connection to a coaxial transmission line and high frequency electrical energy at, for example, one gigahertz is fed to the transducer. The high frequency electric field produced between the thin conductive films 34 and 35 excites the piezoelectric semiconductor material 33 and by virtue of the piezoelectric effect, a substantial portion of the electrical energy is converted to acoustic energy of the same frequency. This acoustic energy is transmitted through the conductive film 34 and into the epitaxial strip delay line 2 by virtue of the contiguous contact therebetween and produces in the strip an acoustic wave of the same frequency which travels through the length of the strip to an output transducer at the other end thereof. The output transducer may be identical to the input transducer shown in FIG. 9 and operates in a reciprocal fashion to convert the acoustic wave energy incident upon the piezoelectric film thereof into high frequency electrical waves.

The transducer 41 as shown in FIG. 10 includes two thin films 42 and 43 of, for example, gold sandwiching the piezoelectric semiconductor material 44. One film 42 connects to the active element of a high frequency transmission line and the other 43 is contiguous with an extension 45 of the epitaxial strip delay line 2 and may be electrically grounded as shown. The exciting high frequency electric field bounded by the conductive films 42 and 43 produces, by virtue of the piezoelectric

effect, high frequency acoustic waves in the semiconductor material 44 which flow parallel to the exciting field and so these high frequency acoustic waves are launched into the extension 45 in a direction substantially parallel to the longitude or length of the epitaxial strip delay line 2. For this purpose, the surface 46 of the extension 45 may be contoured or tapered so that the high frequency acoustic waves at one end thereof will be channeled into the epitaxial strip delay line 2 and will propagate through the delay line in the longitudinal mode.

In FIG. 11, the transducer 51 consists of a thin epitaxial layer 52 of piezoelectric semiconductor material of substantially the same thickness as epitaxial strip delay line 2 and is disposed between two electrically conductive layers 53 and 54 of the same thickness and which may be of gold. The gold layer 53 is preferably grounded and connected to the base 55 of a coaxial connector 56. The center conductor 57 of the coaxial connector couples to the conductive film 54. These conductive films 53 and 54 serve to bound the excitation high frequency electric field imposed on the piezoelectric semiconductor film 52 and which gives rise to the high frequency acoustic waves in the semiconductor. The conductive film 53 may be of material selected to provide an acoustic impedance match between the semiconductor material 52 and the epitaxial strip delay line 2. In the event, these are already reasonably matched acoustically and the strip is composed of an electrically conductive material, then the abutting end of the strip may serve as the exciting electric field boundary. In either event, it is preferred that the strip 2 and the conductive film 53 adjacent the strip be grounded and connected to the outer conductor of the coaxial connector and it is preferred that the center conductor of the coaxial connector connect to the other conductive film 54.

In operation, the high frequency electric field produced in the piezoelectric semiconductor film 52 is parallel to the longitude of the strip delay line 2 and so the acoustic waves generated in the piezoelectric strip 52 are incident upon the end of the delay line 2 normal thereto. Normal incidence is preferred so that the incident waves are conducted by the strip in the first longitudinal mode.

Taps may be provided along the epitaxial strip delay line 2 and may consist of piezoelectric semiconductor transducers which function similarly to the input transducer 51. Tow such taps denoted A and B are shown along the delay line 2 in FIG. 11. Tap A consists of a strip 59 of piezoelectric material running transverse to the delay line 2. This piezoelectric strip 59 may be of the same thickness as the delay line or it may be thicker. However, the strip 59 is preferably only a few microns wide, or as wide as necessary to produce adequate high frequency electric signal levels in electrically conductive transverse strips 60 and 61 disposed in relationship thereto so as to bound a dc electric field applied to the strip 59 in a direction substantially parallel to the length of the delay line 2. For this purpose, the electrically conductive strips 60 and 61 may be formed in the thin film layers 12 and also run transverse to the delay line 2 contiguous with the transverse edges of the piezoelectric strip 59.

The circuit 62 for tap A connected to the conductive strips 60 and 61 could include a dc source 63 in series with a transformer 64. In operation, the dc electric field bounded by the strips 60 and 61 has a fringing field which encompasses the piezoelectric strip 59 and is directed parallel to the length of the delay line 2. High frequency acoustic waves conducted along the delay line through the strip 59 transverse thereto generate high frequency electric signals in the conductive strips 60 and 61 and these are coupled to an output for tap A via the transformer 64. A similar transducer for feeding the output tap B is located at another position along the epitaxial strip delay line 2. Thus, a plurality of taps at different delay positions along the delay line may be provided to form a multi-tap delay line for use in, for example, a pulse compression radar system.

FIGS. 12 and 13 are isometric views of two convenient conformations for providing a relatively long acoustic delay path contained in a space of substantially smaller dimensions than the length of the path. In FIG. 12, the epitaxial strip delay line 71 is formed employing any of the techniques and structures already described, on a cylindrically shaped substrate body 72 in such a manner that the epitaxial strip delay line forms a helix thereon. At one end of this helix is mounted the input transducer 73 and a coupling 74 for connection to a transmission line and at the other end is mounted the output transducer 75 with a coupling 76 for a transmission line.

In FIG. 13, the epitaxial strip delay line 77 is formed on a relatively flat surface of a substrate body 78 and defines a spiral. The input transducer 79 may be located at the center of the spiral and output transducer 80 may be located at the edge of the spiral.

This completes descriptions of a number of embodiments of the present invention of an ultrasonic delay line consisting of an epitaxial layer of unitary crystalline material having a center of inversion symmetry, deposited on a suitable substrate so that high frequency acoustic waves launched into one end of the epitaxial strip are conducted therethrough and experience a high degree of reflection from the major surfaces thereof, and are converted at another end of the epitaxial layer into high frequency electric waves such that the delay therebetween is predetermined and significant for a useful purpose. The embodiments described herein illustrate but a few applications of principle features of the invention and are not intended to limit the spirit and scope of the invention as set forth in the accompanying claims.

What is claimed is:

1. A dispersive ultrasonic delay line comprising

a substrate body;

an epitaxial layer attached to said substrate body, comprising a single unitary crystalline material having a center of inversion symmetry and in which microwave ultrasonic material waves experience tolerable attenuation per unit length of the material, having a thickness of the same order of magnitude as the inflection thickness for said material at a preselected microwave frequency, and having major and minor surfaces,

means for forming substantially reflective interfaces with substantial portions of said major surfaces of said epitaxial layer,

means for launching longitudinal ultrasonic material waves into said epitaxial layer at a first portion thereof, and

means for detecting said ultrasonic material waves in said epitaxial layer at a second portion thereof remote from said first portion.

2. Apparatus as recited in claim 1 wherein

said substantially reflective interfaces define the boundaries of a path along the longitudinal axis of said epitaxial layer along which said ultrasonic material waves are conducted from said launching means to said detecting means.

3. Apparatus as recited in claim 1 further including

an acoustic wave absorbing means abutting at least one minor surface of said epitaxial layer.

4. Apparatus as recited in claim 1 wherein

said epitaxial layer is formed of a material selected from the group of single unitary crystalline materials having a center of inversion symmetry consisting of

sapphire

rutile

spinel

zirconium silicate, and

zirconate.

5. Apparatus as recited in claim 1 wherein

said substantially reflective interface forming means comprises a plurality of contiguous layers of alternately high and low acoustic impedance disposed adjacent and substantially parallel to said epitaxial layer, each contiguous layer being of a thickness equal to one quarter wavelength at said preselected microwave frequency.

6. Apparatus as recited in claim 1 wherein

said epitaxial layer is in the form of an epitaxial membrance and the major surfaces of said membrane are adjacent a gas.

7. Apparatus as recited in claim 1 wherein

said epitaxial layer is in the form of an epitaxial membrane and the major surfaces of said membrane are adjacent a vacuum.

8. Apparatus as recited in claim 1 wherein

said substrate body has a substantially cylindrical configuration, and

said epitaxial layer is formed in a helical path about said cylindrical substrate body.

9. Apparatus as recited in claim 1 wherein

said epitaxial layer is formed in a planar spiral path for conducting said ultrasonic material waves.

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