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(54) ULTRASONIC PROBE

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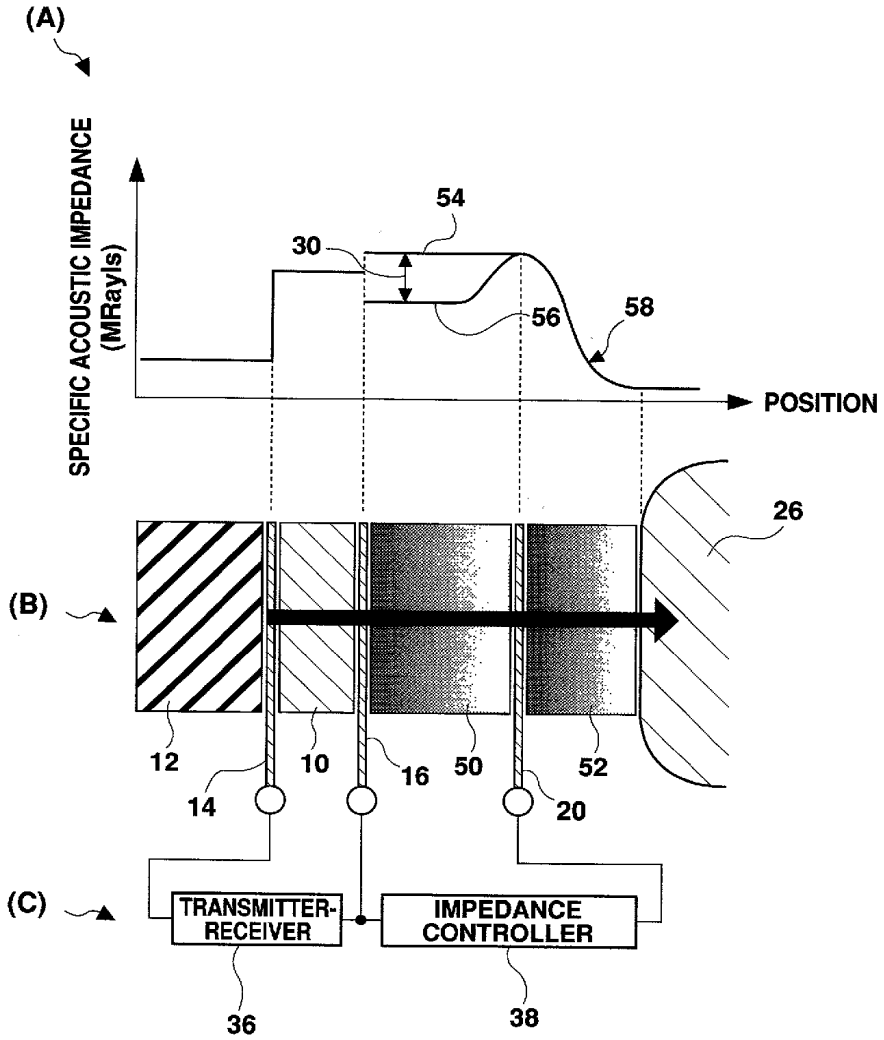
(57) **ABSTRACT**

An ultrasonic probe which is used for ultrasonic diagnosis comprises a transducer element, a sonic speed control element, and an acoustic matching layer. The sonic speed control element has a function to control the sonic speed of the ultrasonic waves traveling therethrough, and has an inclined characteristic in the sonic speed control effect in which the sonic speed control effect changes continuously along the direction of travel of the ultrasonic waves (thickness direction). The specific acoustic impedance of the sonic speed control element at the end near the living body corresponds to the specific acoustic impedance of the acoustic matching layer at the end away from the living body. The acoustic matching layer is preferably formed by layering 2 or 3 or more overlapped members. The boundary between two adjacent members has a shape with a plurality of hills and valleys. The crossing angle between the direction of travel of the ultrasonic waves and the boundary is set so that a predetermined condition is satisfied.



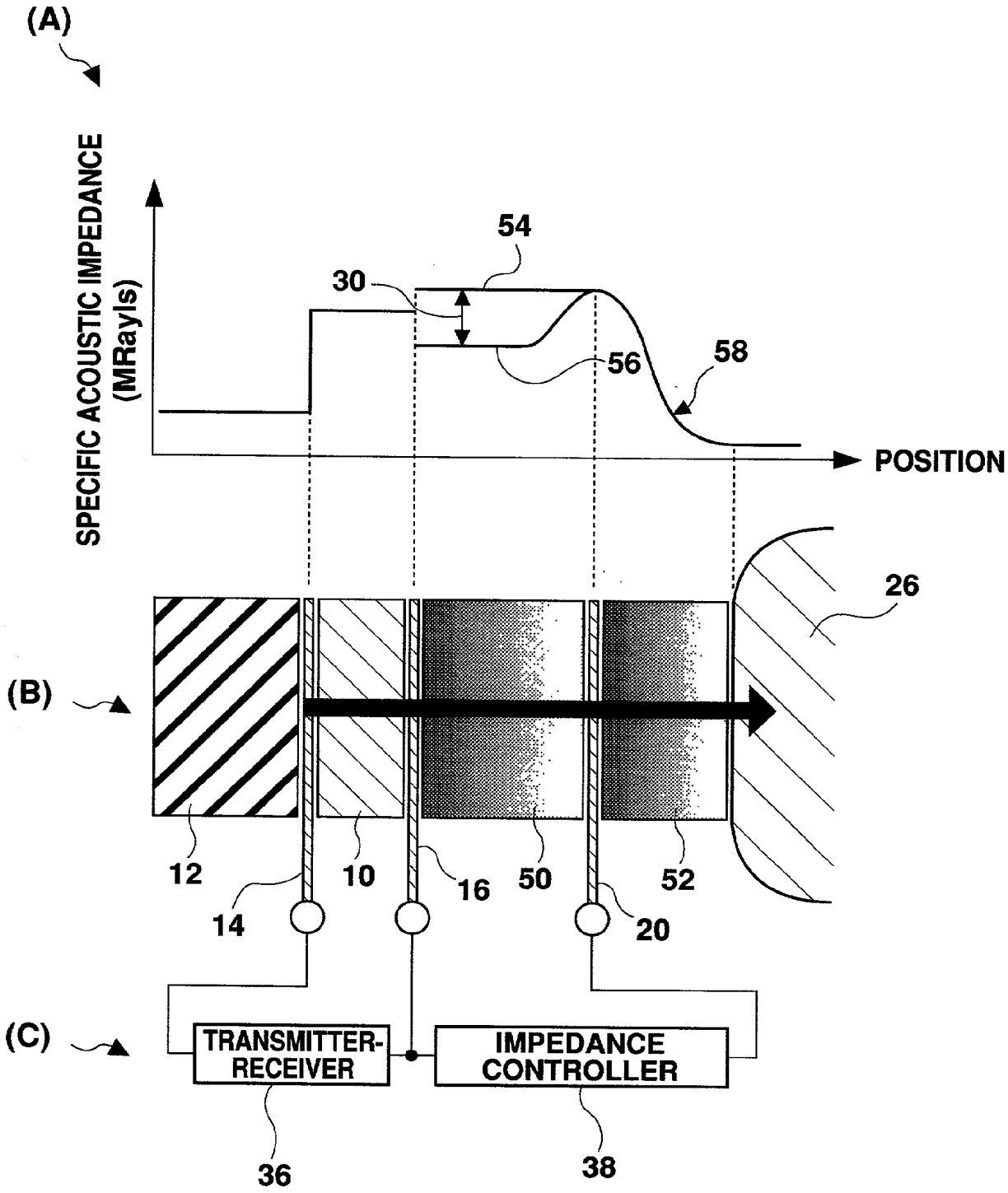

(A)
SPECIFIC ACOUSTIC IMPEDANCE (MRayls)
54
30
56
58
POSITION
26
(B)
12
10
16
50
52
14
20
(C)
TRANSMITTER-RECEIVER
IMPEDANCE CONTROLLER
36
38

Fig. 1

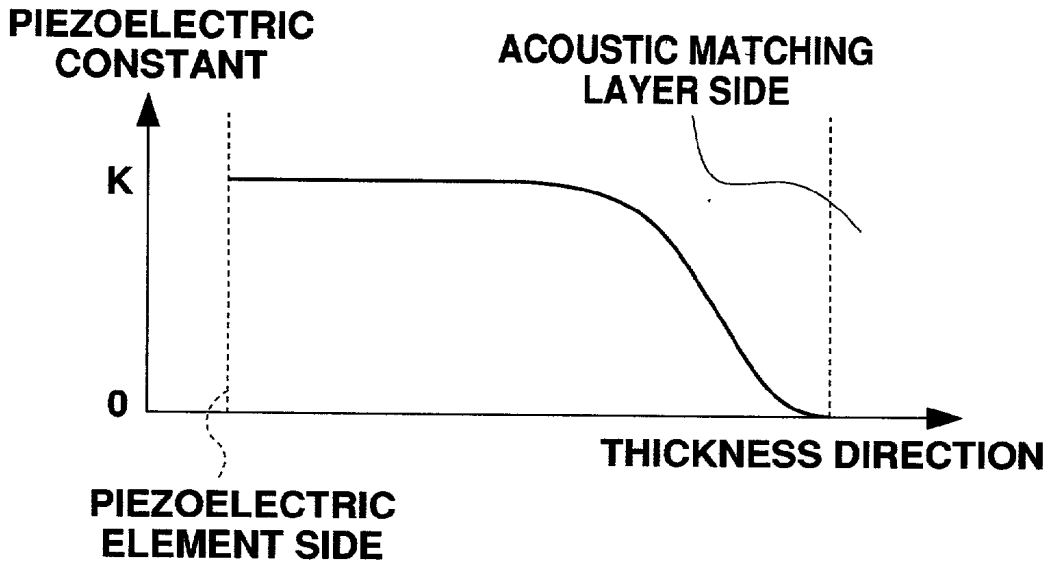


Fig. 2

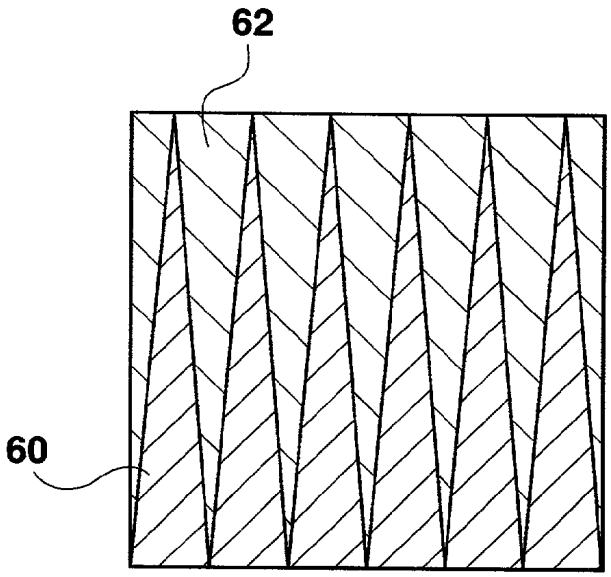


Fig. 3

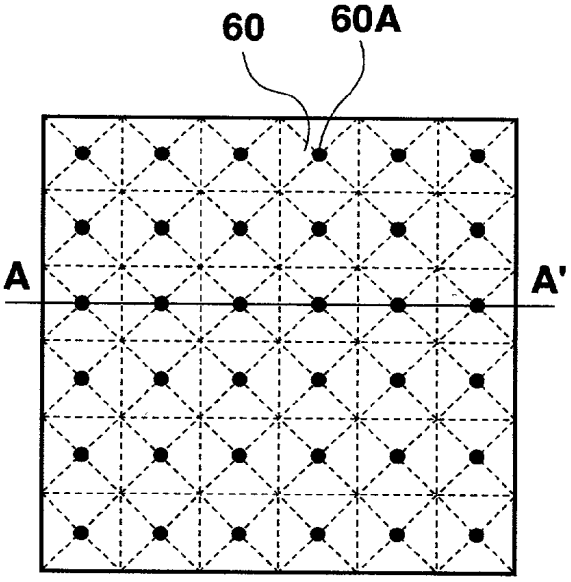


Fig. 4

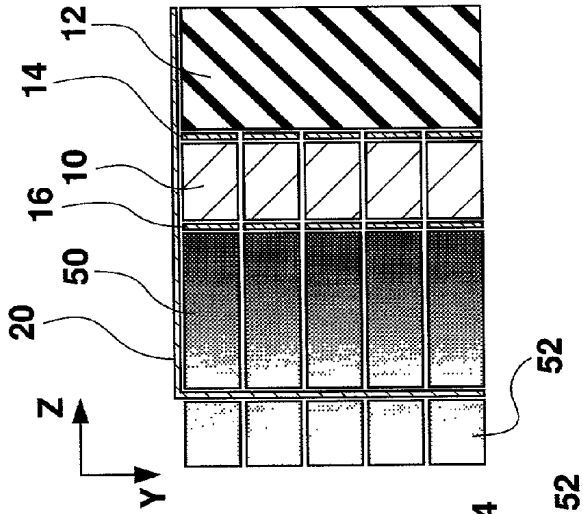


Fig. 7

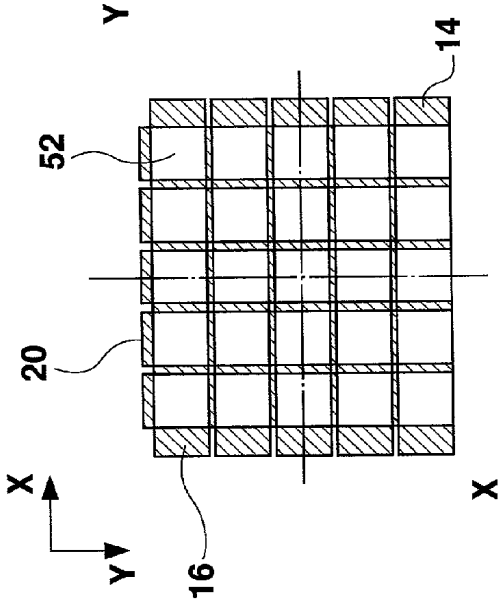


Fig. 5

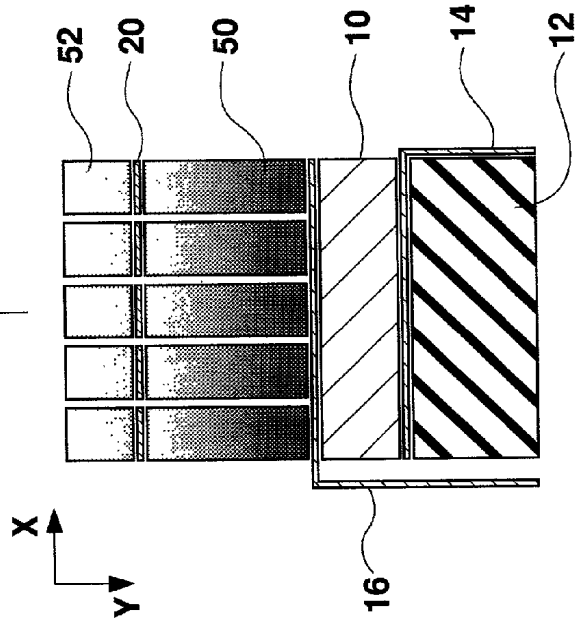


Fig. 6

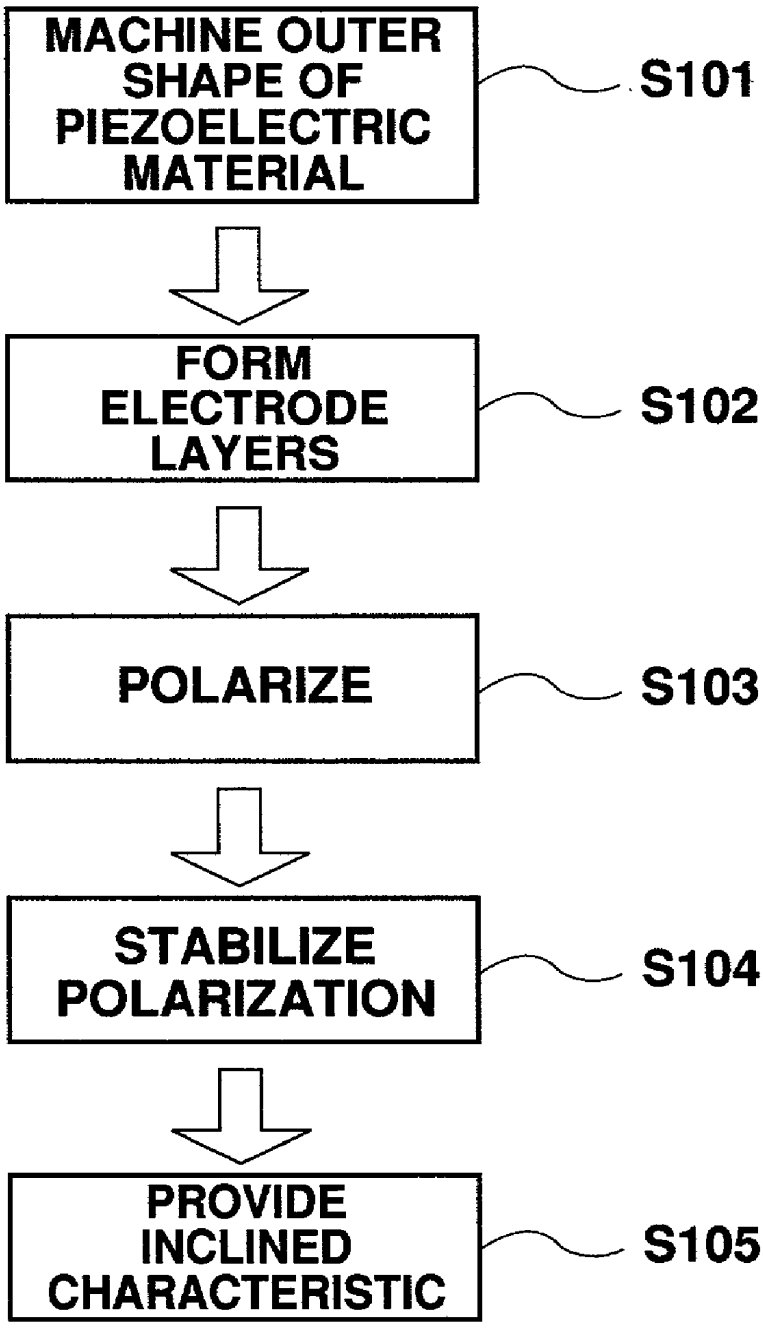

MACHINE OUTER SHAPE OF PIEZOELECTRIC MATERIAL
S101
FORM ELECTRODE LAYERS
S102
POLARIZE
S103
STABILIZE POLARIZATION
S104
PROVIDE INCLINED CHARACTERISTIC
S105

Fig. 8

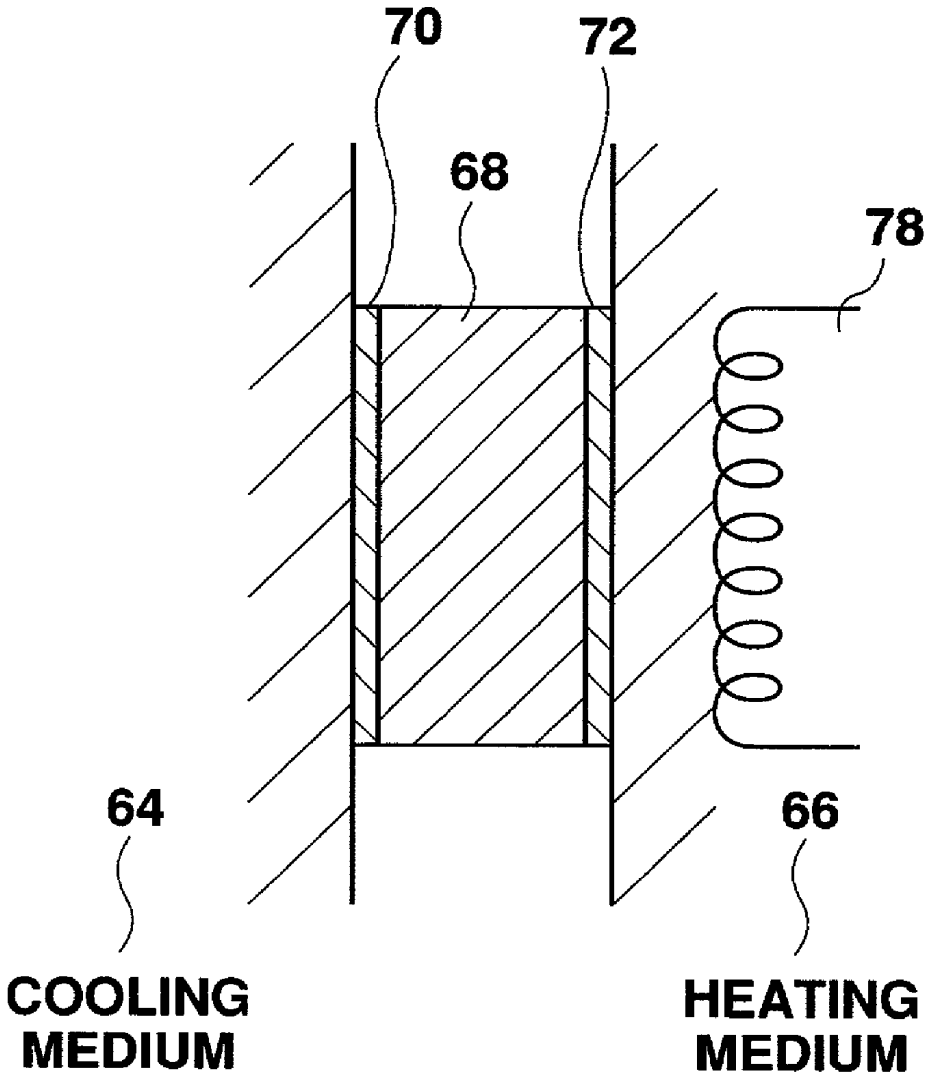


Fig. 9

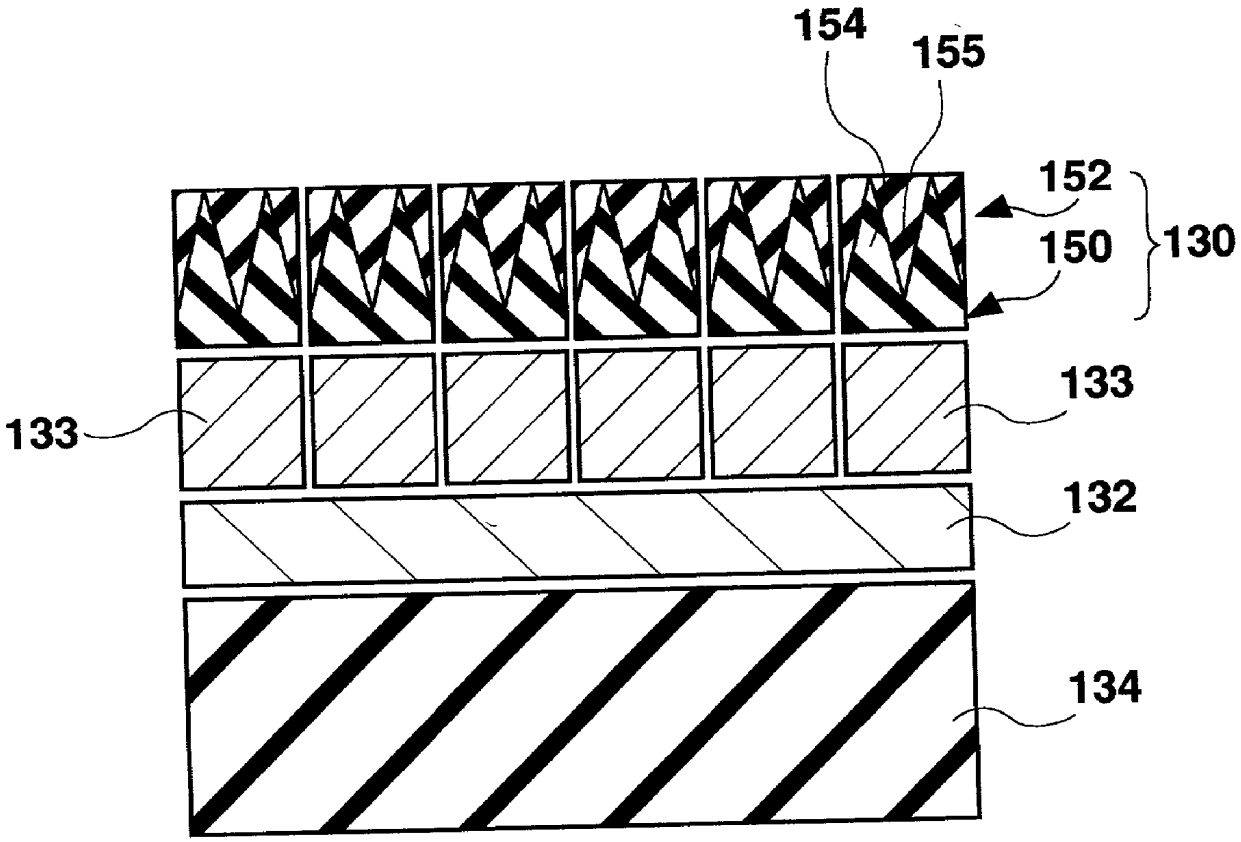


Fig. 10

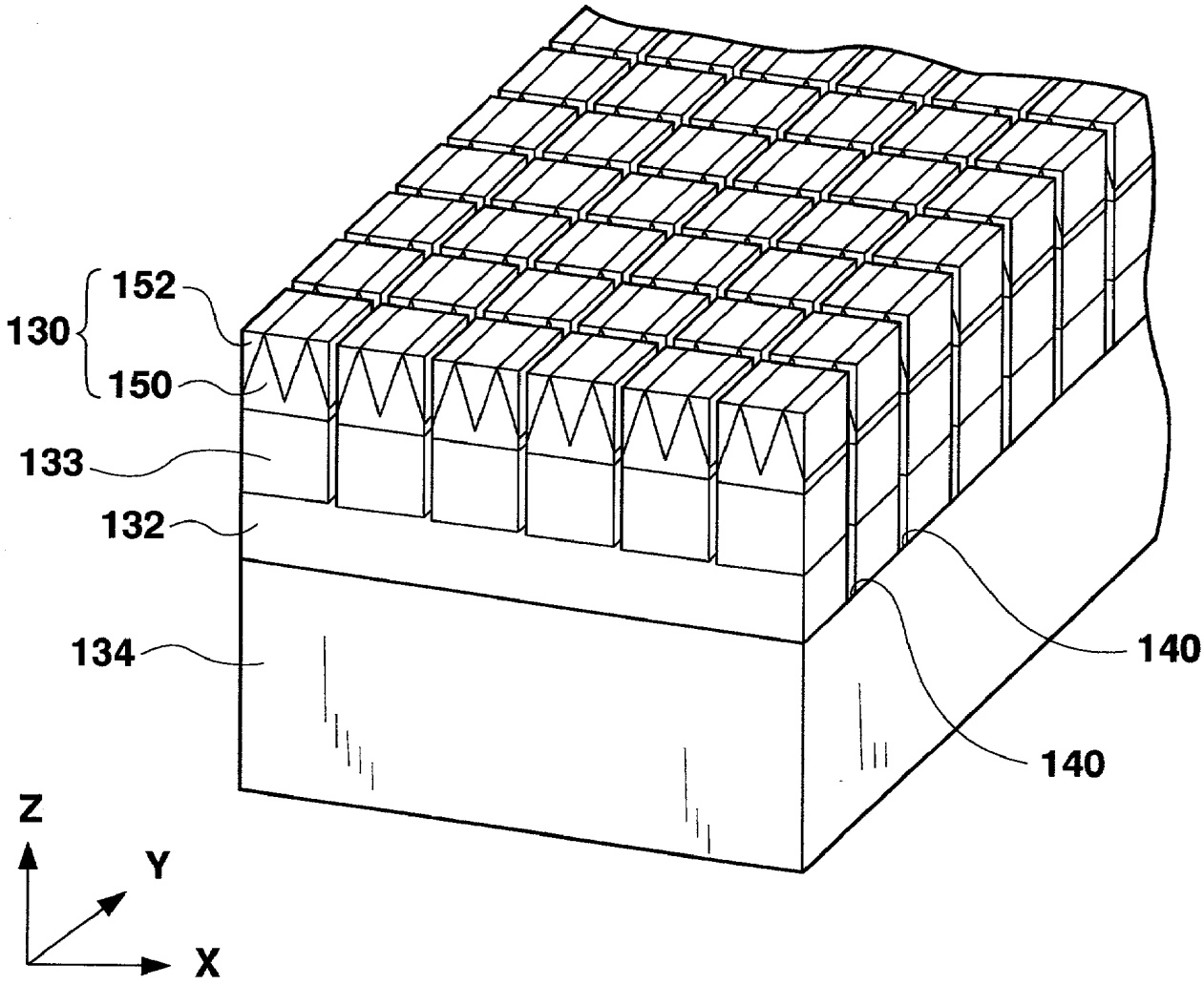


Fig. 11

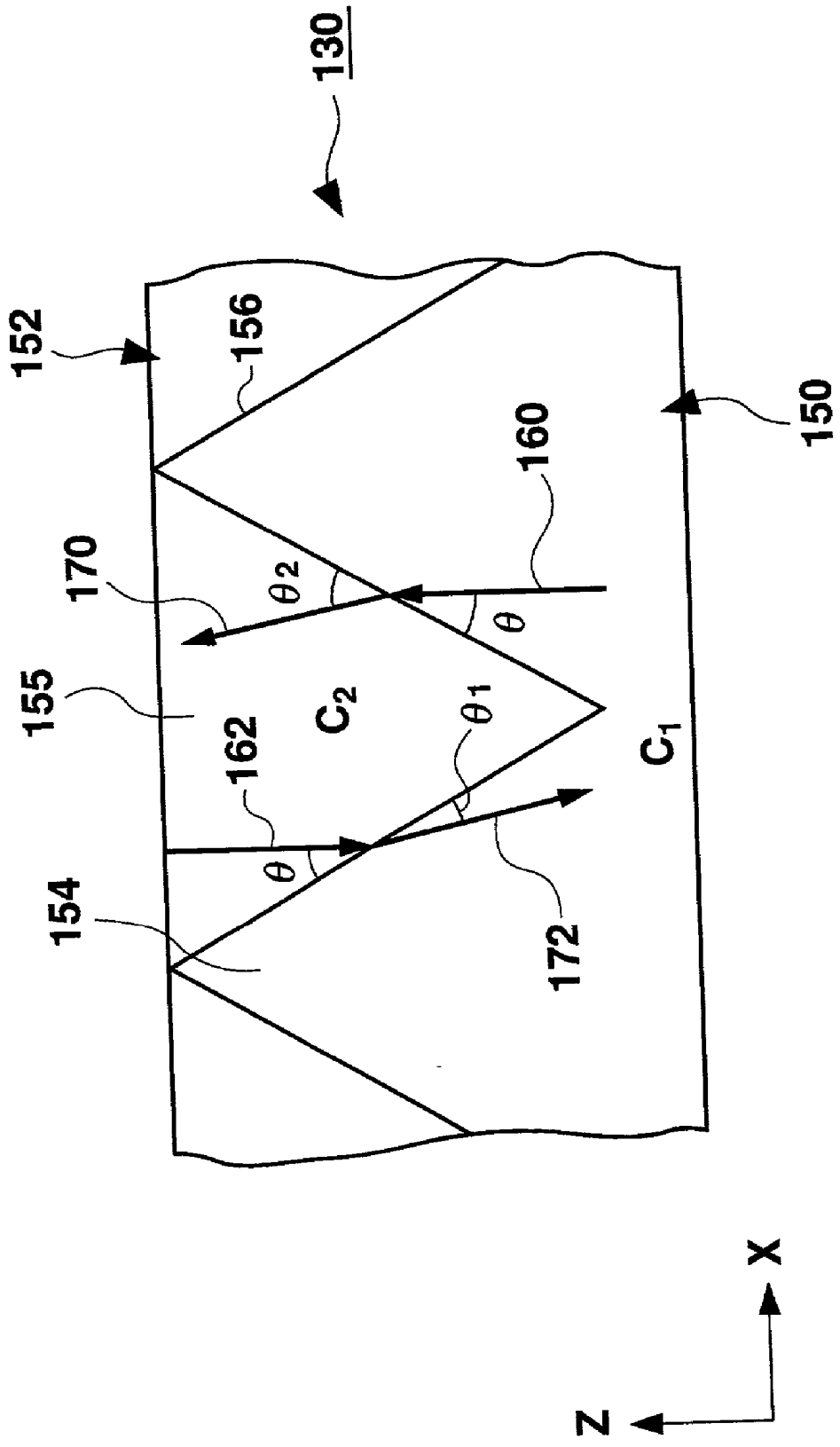

130
152
156
150
160
170
θ_2
θ
155
C_2
θ_1
C_1
162
θ
154
172
X
Z

Fig. 12

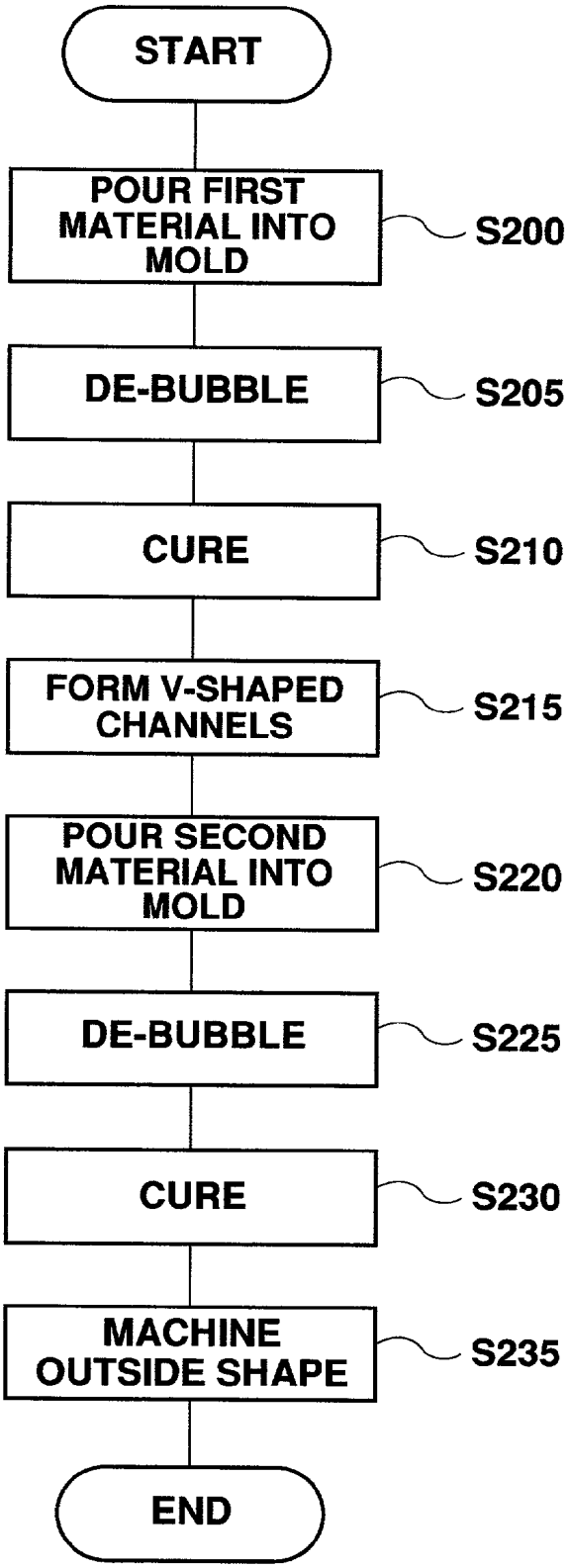

START
POUR FIRST MATERIAL INTO MOLD
S200
DE-BUBBLE
S205
CURE
S210
FORM V-SHAPED CHANNELS
S215
POUR SECOND MATERIAL INTO MOLD
S220
DE-BUBBLE
S225
CURE
S230
MACHINE OUTSIDE SHAPE
S235
END

Fig. 13

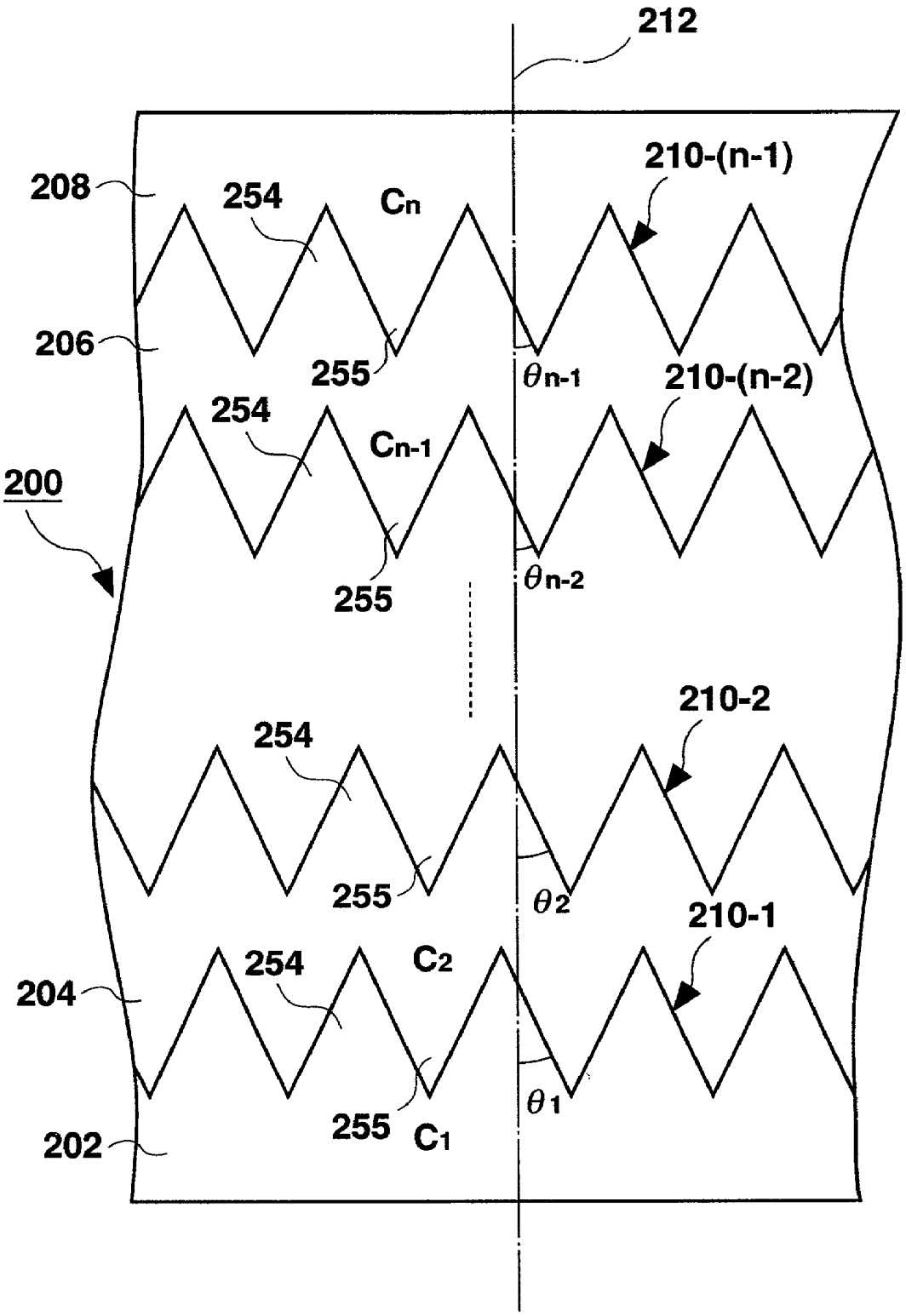

212
208
254
Cn
210-(n-1)
206
255
θn-1
210-(n-2)
254
Cn-1
200
255
θn-2
210-2
254
255
θ2
210-1
254
C2
204
θ1
255
C1
202

Fig. 14

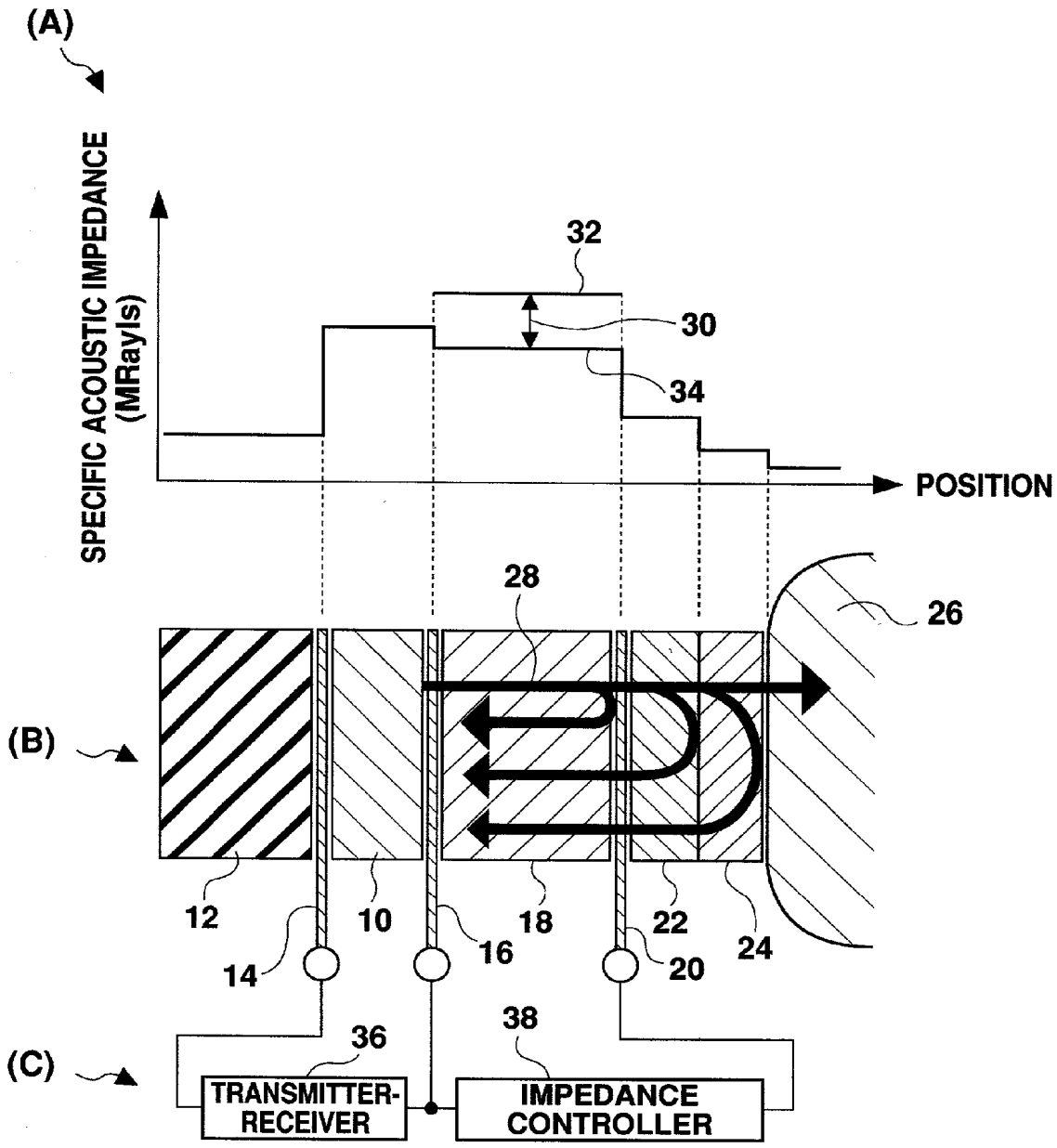


Fig. 15 PRIOR ART

ULTRASONIC PROBE

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to an ultrasonic probe and, more particularly, to an ultrasonic probe having a sonic speed control element.

[0003] 2. Description of the Related Art

[0004] In ultrasonic diagnosis, in general, an ultrasonic probe is brought into contact with a surface of a living body and an ultrasonic wave is transmitted and/or received in that state. Japanese Patent Laid-Open Publication No. Hei 11-123188 discloses a new type of an ultrasonic probe which has a sonic speed control element. In this ultrasonic probe, a sonic speed control element is provided on the upper surface of a transducer for transmission/reception of ultrasonic waves. On the upper surface of the sonic speed control element, one or two acoustic matching layers are provided.

[0005] Similar to the transducer, a sonic speed control element is formed from, for example, a piezoelectric material. An external circuit is connected to the sonic speed control element. When the electrical impedance of the external circuit is varied, the ultrasonic propagation characteristic of the sonic speed control element is changed. In other words, mechanical or acoustic delay control which is different from the conventional electrical delay control can be realized through variations in the sonic speed of the ultrasonic waves traveling through the sonic speed control element.

[0006] Japanese Patent Laid-Open Publication No. Hei 11-123188 as described above also discloses more specifically another type of ultrasonic probe. The ultrasonic probe has a 1-D array transducer comprising a plurality of transducer elements. The arrangement direction (array direction) of the plurality of transducers is the electronic scan direction of the ultrasonic beams. A direction perpendicular to the arrangement direction is the elevation direction. In the ultrasonic probe, a plurality of sonic speed control elements which are arranged two-dimensionally is provided on the upper surface (surface near the living body) of the 1-D array transducer. More specifically, a plurality of sonic speed control elements are provided along the elevation direction for each one of the transducer elements. In this structure, for each transducer element, a signal lead is provided individually. A sonic speed control lead is provided individually for each plurality of sonic speed control elements (sonic speed control element column) arranged in the array direction. Further, a plurality of common ground leads are provided between the plurality of transducer elements and the plurality of sonic speed control elements. According to this structure, focus formation for ultrasonic beams, deflection of the ultrasonic beams, and scan of the ultrasonic beams can be realized both in the array direction and in the elevation direction. In other words, an advantage similar to a 2-D array transducer or a 1.5-D array transducer can be obtained. Moreover, there is an additional advantage that the number of signal lines can be significantly reduced compared to the conventional structures.

[0007] However, with the ultrasonic probe according to the above related art, because the specific acoustic impedances of the sonic speed control elements change dynamically, the specific acoustic impedance tends to not match at the boundary between a sonic speed control element and an acoustic matching layer, boundary between two adjacent acoustic matching layers, and boundary between an acoustic matching layer and the living body. When the specific acoustic impedance is not matched at these boundaries, unnecessary reflections of ultrasonic waves are generated at each of the boundaries and multiple reflections of the ultrasonic waves are generated between a plurality of boundaries. As a result, lingering (tailing) occurs in the transmitted ultrasonic waves and in the received ultrasonic waves, causing degradation in resolution in the distance direction. Also, the electrically formed focus and beam patterns are degraded. In summary, the mismatch of the specific acoustic impedance at each boundary causes degradation in the quality of ultrasonic images.

[0008] The above problem will now be described in more detail referring to **FIG. 15**, which shows the prior art. The schematic view shown in **FIG. 15**(B) shows a transducer including a transducer element **10** and a sonic speed control element **18**. A backing layer **12** is provided at the lower side of the transducer element **10** (the side opposite the living body) with a signal lead **14** in between. A sonic speed control element **18** is provided at the upper side of the transducer element **10** (the side near the living body) with a common ground lead **16** in between. At the side of the sonic speed control element **18** near the living body, a first acoustic matching layer **22** and a second acoustic matching layer **24** are provided via a sonic speed control lead **20**. The surface of the second acoustic matching layer **24** near the living body is brought into contact with the living body **26**. As described above, the sonic speed control element **18** controls the sonic speed of ultrasonic waves traveling therethrough to realize acoustic delay.

[0009] As shown in **FIG. 15**(C), a transmitter-receiver **36** is connected between the signal lead **14** and the ground lead **16**. An impedance controller **38** is connected between the sonic speed control lead **20** and the ground lead **16**. The impedance controller **38** has a function such that the electrical impedance of the impedance controller can be varied. The impedance controller **38** and the sonic speed control element **18** form a closed circuit. When the electrical impedance of the impedance controller **38** is varied, the sonic speed of the ultrasonic waves traveling through the sonic speed control element **18** is changed.

[0010] **FIG. 15**(A) shows a graph indicating specific acoustic impedances at each position in the direction of travel of the ultrasonic waves. As shown in the figure, conventionally, the sonic speed control element **18** has a uniform specific acoustic impedance throughout the element. The specific acoustic impedance changes depending on the magnitude of the sonic speed variation. Reference numeral **32** shows a case of a maximum specific acoustic impedance and reference numeral **34** shows a case of a minimum specific acoustic impedance. Reference numeral **30** shows the variation width of the specific acoustic impedance.

[0011] The following problem is present in the related art shown in **FIG. 15**, as shown by reference numeral **28**. The specific acoustic impedance of the end of the sonic speed control element **18** near the living body changes dynamically according to the sonic speed control. On the other

hand, the specific acoustic impedances of the acoustic matching layers **22** and **24** do not dynamically change. Therefore, it is not always possible to match the specific acoustic impedance at the boundary between the sonic speed control element **18** and the acoustic matching layer **22**. That is, a reflection wave which cannot be ignored is produced at this boundary. In addition, in the structure of **FIG. 15**, reflection waves are also produced at the boundaries between the acoustic matching layer **22** and the acoustic matching layer **24** and between the acoustic matching layer **24** and the living body **26**, which also cannot be ignored. Therefore, in order to sufficiently take the advantage of the sonic speed control element, the reflection waves must be removed or reduced.

SUMMARY OF THE INVENTION

[0012] One object of the present invention is to improve the propagation characteristic of ultrasonic waves in an ultrasonic probe having a sonic speed control element.

[0013] Another object of the present invention is to enhance the quality of ultrasonic images.

[0014] Yet another object of the present invention is to provide an acoustic matching layer adapted for a sonic speed control element.

[0015] (1) In order to achieve at least one of the objects mentioned above, according to a first aspect of the present invention, there is provided an ultrasonic probe comprising a transducer element for transmitting and receiving ultrasonic waves; a sonic speed control element provided at the side of the transducer element near a living body and through which the ultrasonic waves transmitted or received by the transducer element travel, the sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough and having an inclined characteristic in the sonic speed control effect in which the sonic speed control effect is gradually changed along the direction of travel of the ultrasonic waves over the whole sonic speed control element or in a portion of the sonic speed control element in the direction of travel; and an acoustic matching layer provided at the side of the sonic speed control element near the living body.

[0016] According to the above structure, the inclined characteristic in the sonic speed control effect of the sonic speed control element can be used to solve or alleviate the problems of specific acoustic impedance mismatches as described above. For example, it is possible to set the sonic speed control effect in the sonic speed control element so that it is gradually decreased towards the living body, eventually to zero or a value close to zero at the end near the living body. In this case, the specific acoustic impedance at the end of the sonic speed control element near the living body is a constant value (or near a constant value with small variation) regardless of the sonic speed control operation. Thus, acoustic matching can more easily be achieved at the boundary between the end of the sonic speed control element near the living body and the acoustic matching layer.

[0017] The transducer is constructed from, for example, a piezoelectric material such as a PZT and a composite material. Similarly, the sonic speed control element is also constructed from, for example, a piezoelectric material such as a PZT and a composite material.

[0018] When the sonic speed control effect is varied in the above structure along the direction of travel of the ultrasonic waves (thickness direction), it is preferable that the variation be continuous, but a step-wise variation is also possible.

[0019] An electrode or a lead is provided as necessary between the transducer element and backing layer, between the transducer element and sonic speed control element, and between the sonic speed control element and acoustic matching layer. It is preferable that the thickness of these electronic elements be thin with respect to the wavelength λ of the ultrasonic waves such that the thickness of these elements may be essentially ignored. With such a structure, the problem caused by the presence of these electronic elements, that is, mismatches in the specific acoustic impedance, can be prevented.

[0020] The present invention can be applied to various types of transducers such as a 1-D array transducer (used when a fixed focus is set in the elevation direction), a 1.5-D array transducer (used when variable focusing is executed in the elevation direction), and a 2-D array transducer (used in a case where beam scan is performed in two perpendicular directions). The present invention can be adapted for various electronic scan methods such as, for example, electronic linear scan and electronic sector scan.

[0021] According to another aspect of the present invention, it is preferable that the specific acoustic impedance characteristic within the acoustic matching layer is set based on the specific acoustic impedance of the sonic speed control element at the end near a living body and the specific acoustic impedance of the living body. With such a structure, unnecessary reflections of ultrasonic waves can be removed or reduced at the boundaries between the acoustic matching layer and sonic speed control element and between the acoustic matching layer and living body.

[0022] According to another aspect of the present invention, it is preferable for the sonic speed control effect of the sonic speed control element to be gradually reduced from the side of the sonic speed control element away from the living body towards the end of the sonic speed control element near the living body, and for the specific acoustic impedance of the acoustic matching layer to correspond to the specific acoustic impedance of the end of the sonic speed control element near the living body.

[0023] According to yet another aspect of the present invention, it is preferable that the sonic speed control element be made of a piezoelectric material, and that the piezoelectric constant of the piezoelectric material changes along the direction of travel. By varying the piezoelectric constant along the direction of travel of the ultrasonic waves (thickness direction), the sonic speed control effect (degree of sonic speed control) at each position in the direction of travel can be varied, and, at the same time, the amount of variation in the specific acoustic impedance at each position in the direction of travel can be manipulated.

[0024] When a sonic speed control element is manufactured, it is possible to employ a process, for example, in which, first, the entire piezoelectric material is polarized, then, thin electrode layers are formed on both surfaces of the piezoelectric material, and a cooling medium is contacted to

a first surface of the piezoelectric material and a heating medium is contacted to a second surface of the piezoelectric material for partial polarization vanishing process. In this case, an inclined characteristic in the polarizability can be obtained in which the polarizability continuously varies from a value of zero near the second surface towards the first surface. In other words, the portion of the piezoelectric material near the second surface has a piezoelectric constant of approximately zero, and a gradient in the piezoelectric constant is created from this portion towards the first surface.

[0025] According to another aspect of the present invention, it is preferable that the piezoelectric constant at the end of the sonic speed control element near the living body is zero. In other words, at the end of the sonic speed control element near the living body, the sonic speed does not change regardless of the sonic speed control, and the specific acoustic impedance also does not vary. Because of this, by coinciding the specific acoustic impedance of the acoustic matching layer with that of the end of the sonic speed control element near the living body, the specific acoustic impedance can always be matched at the boundary between the acoustic matching layer and the sonic speed control element regardless of the sonic speed control.

[0026] According to another aspect of the present invention, it is preferable that the piezoelectric constant gradually decreases from the middle portion of the sonic speed control element towards the end of the sonic speed control element near the living body. It is also possible to vary the piezoelectric constant entirely along the direction of travel of the ultrasonic waves, but in order to match the specific acoustic impedance at the boundary between the acoustic matching layer and the sonic speed control element, it is sufficient to partially reduce the piezoelectric constant. Further, instead of varying the piezoelectric constant, it is also possible to mix a high dielectric constant, non-piezoelectric material into the sonic speed control element, with the amount of mixing varied along the thickness direction of the sonic speed control element.

[0027] According to another aspect of the present invention, it is preferable that the piezoelectric constant gradually decreases from the middle portion of the sonic speed control element towards the end of the sonic speed control element near the living body and towards the end of the sonic speed control element away from the living body. According to a further aspect of the present invention, it is preferable that the piezoelectric constants at the ends of the sonic speed control element near the living body and away from the living body are zero.

[0028] According to another aspect of the present invention, it is preferable that the acoustic matching layer has an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance gradually changes from the end away from the living body toward the end near the living body. In this manner, by also providing an inclined characteristic in the specific acoustic impedance for the acoustic matching layer, unnecessary reflection of ultrasonic waves can be further reduced and the quality of the ultrasonic images can be improved.

[0029] According to another aspect of the present invention, it is preferable that the specific acoustic impedance of the end of the acoustic matching layer away from the living body matches with the specific acoustic impedance of the end of the sonic speed control element near the living body; and the specific acoustic impedance of the end of the acoustic matching layer near the living body matches with the specific acoustic impedance of the living body.

[0030] According to another aspect of the present invention, it is preferable that the acoustic matching layer comprises a first member and second member having different specific acoustic impedances from each other; and that the compositional ratio between the first member and the second member changes along the direction of travel. Here the compositional ratio refers to the ratio of presence per unit volume.

[0031] According to yet another aspect of the present invention, it is preferable that the first member has a specific acoustic impedance which is equal to the specific acoustic impedance of the end of the sonic speed control element near the living body, and that the second member has a specific acoustic impedance which is equal to the specific acoustic impedance of the living body. The first member can be formed from, for example, a material similar to the sonic speed control element (but a non-polarized material). The second member can be, for example, a composite material in which an additive such as silica is added to a base material such as liquid phase silicone. In this case, the specific acoustic impedance of the second member can be adjusted by adjusting the amount of the added additive.

[0032] According to another aspect of the present invention, it is preferable that the first member comprises a plurality of pyramid elements having a pinnacle shape projecting towards the living body; and that the second member is filled into the gap between the plurality of pyramid elements. The pyramid element may be a quadrangular pyramid or hexagonal pyramid. It is preferable that the arrangement pitch of the plurality of pyramid elements be sufficiently small compared to the wavelength λ of the ultrasonic waves, and can be, for example, less than or equal to $\lambda/5$. The plurality of pyramid elements can be formed through various methods such as, for example, cutting, pressing, or etching applied on a plate-shaped first member.

[0033] Furthermore, the sonic speed control elements can have a similar structure. That is, it is possible to form a plurality of pyramid elements from a piezoelectric material and fill a non-piezoelectric material having a high dielectric constant into the gaps.

[0034] (2) In order to achieve at least one of the objects mentioned above, according to the present invention, there is provided an ultrasonic probe comprising N transducer elements for transmitting and receiving ultrasonic waves; N×M sonic speed control elements provided at the ends of the N transducer elements near the living body and through which the ultrasonic waves travel, with M sonic speed control elements provided for each transducer element, each sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough and having an inclined characteristic in the sonic speed control effect in which the sonic speed control effect gradually changes along the direction of travel of the ultrasonic waves over the whole sonic speed control element or in a portion of the sonic speed control element in the direction of travel; and N×M acoustic matching layers

provided at the side of the N×M sonic speed control elements near the living body.

[0035] (3) In order to achieve at least one of the objects mentioned above, according to the present invention, there is provided an ultrasonic probe comprising a transducer element for transmitting and receiving ultrasonic waves; a sonic speed control element provided at the side of the transducer element near the living body and through which the ultrasonic waves travel, the sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough; and an acoustic matching layer provided at the side of the sonic speed control element near the living body and having an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance monotonically changes along the direction of travel of the ultrasonic waves.

[0036] According to another aspect of the present invention, it is preferable that the sonic speed control element has a non-inclined characteristic in the sonic speed control effect in which the sonic speed control effect is uniform at every position in the direction of travel. Even if the sonic speed control element has a non-inclined characteristic (that is, uniform characteristic) in the specific acoustic impedance, by providing, corresponding to the sonic speed control element, an acoustic matching layer in which the specific acoustic impedance monotonically varies, unnecessary reflections of ultrasonic waves can be reduced and the sonic speed control element can function satisfactorily.

[0037] According to another aspect of the present invention, it is preferable that the sonic speed control element has an inclined characteristic in the sonic speed control effect in which the sonic speed control effect gradually changes along the direction of travel. With such a structure, the propagation efficiency of the ultrasonic waves can be improved by the inclined characteristic in the sonic speed control effect of the sonic speed control element and the inclined characteristic in the specific acoustic impedance of the acoustic matching layer.

[0038] According to another aspect of the present invention, it is preferable that the acoustic matching layer comprises a first member and a second member overlapped in the direction of travel; the first member and the second member have different specific acoustic impedances from each other; and the boundary between the first member and the second member has a shape with a plurality of hills and valleys.

[0039] According to another aspect of the present invention, it is preferable that when the crossing angle between the direction of travel and the boundary is θ, the sonic speed of the ultrasonic waves within the first member is C_1, and the sonic speed of the ultrasonic waves within the second member is C_2, a condition,

$$C_2<C_1<C_2/\cos\theta \quad \text{(Equation 1)}$$

[0040] or a condition,

$$C_2=C_1 \quad \text{(Equation 2)}$$

[0041] is satisfied.

[0042] When the above equation (2) is satisfied, that is, when the sonic speeds in two members (two sub-layers) forming the acoustic matching layer are equal, no refraction or total internal reflection is produced at the boundary between the two members in accordance with Snell's law.

[0043] On the other hand, when the above equation (2) is not satisfied, that is, when the sonic speeds differ in the two members forming the acoustic matching layer, the following is true. Here, a "first member" is defined as the member in which the sonic speed is larger among the two members forming the acoustic matching layer and a "second member" is defined as the member in which the sonic speed is smaller.

[0044] Under the above condition, $C_2<C_1$, when an ultrasonic wave is incident from the first member into the second member, no total internal reflection of the ultrasonic wave is generated regardless of the size of θ, in accordance to Snell's law. In contrast, when an ultrasonic wave is incident from the second member, in which the sonic speed is smaller, to the first member, in which the sonic speed is larger, whether or not a total internal reflection is generated at the boundary depends on the incident angle of the ultrasonic wave with respect to the boundary. Here, the direction of the actual propagation of the ultrasonic waves is primarily in the direction of normal with respect to the surface of the acoustic matching layer (thickness direction). The direction is already defined as the direction of travel. A condition in equation (1), $C_1<C_2/\cos\theta$, is for preventing the total internal reflection when ultrasonic waves are incident from the second member into the first member along the direction of normal. The slope of each of the sections (each surface elements) is determined to satisfy equation (1).

[0045] More specifically, the hills-and-valleys surface shape of the boundary and the sonic speeds in the first and second members are determined to satisfy the equations (1) or (2). In this manner, the generation of total internal reflection can be prevented or inhibited for both cases of transmission and reception of ultrasonic waves.

[0046] In addition, it is possible to design the acoustic matching layer so that the transmitted ultrasonic waves are incident from the first member into the second member, or, alternatively, from the second member into the first member.

[0047] According to another aspect of the present invention, it is preferable that one member, of the first member and the second member, provided near the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of the living body; and the other member of the first member and the second member provided away from the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of the sonic speed control element.

[0048] According to a further aspect of the present invention, it is preferable that one member of the first member and the second member comprises a plurality of first elements having a pinnacle shape; and the other member of the first member and the second member comprises a plurality of second elements having a shape to fit in the valley section between the plurality of first elements.

[0049] According to yet another aspect of the present invention, it is preferable that the pinnacle shape is a shape with a triangular vertical cross section and a quadrangle horizontal cross section, a pyramid shape, or the like.

[0050] According to another aspect of the present invention, it is preferable that the arrangement pitch of the

plurality of first elements is less than or equal to ½ of the wavelength of the ultrasonic waves. According to another aspect of the present invention, it is preferable that the depth of the valley section is greater than or equal to ½ of the wavelength of the ultrasonic waves.

[0051] (4) In order to achieve at least one of the objects mentioned above, according to the present invention, there is provided an ultrasonic probe, comprising a transducer element for transmitting and receiving ultrasonic waves; a sonic speed control element provided at the side of the transducer element near the living body and through which the ultrasonic waves travel, the sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough; and an acoustic matching layer provided at the side of the sonic speed control element near the living body and having an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance monotonically changes along the direction of travel, the acoustic matching layer made of n members (where n is an integer greater than or equal to 3) overlapped in the direction of travel, and the specific acoustic impedances of the n members changing in steps along the direction of travel.

[0052] According to another aspect of the present invention, it is preferable that each of the boundaries between the n members has a shape with hills and valleys.

[0053] According to another aspect of the present invention, it is preferable that when the crossing angle between the direction of travel and the boundary between the k-th member (where k is an integer satisfying the condition, $1 \leqq k \leqq (n-1)$) and (k+1)-th member is θ_k, the sonic speed of the ultrasonic waves within the k-th member is C_k, and the sonic speed of the ultrasonic waves within the (k+1)-th member is C_{k+1}, a condition,

$$C_{k+1}<C_k<C_{k+1}/\cos\theta_k$$

[0054] or a condition,

$$C_{k+1}=C_k$$

[0055] is satisfied.

[0056] With such a structure, in an acoustic matching layer comprising three or more members (sub-layers), the specific acoustic impedance can substantially be continuously varied along the direction of travel of the ultrasonic waves. That is, an inclined characteristic in the specific acoustic impedance can be provided for the acoustic matching layer. Thus, total internal reflection produced at the boundary can be inhibited and the proper function of the sonic speed control element can be sufficiently achieved.

[0057] According to another aspect of the present invention, it is preferable that the member, among the n members, that is closest to the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of the living body; and the member, among the n sub-layers, that is closest to the sonic speed control element has a specific acoustic impedance corresponding to the specific acoustic impedance of the sonic speed control element.

[0058] According to another aspect of the present invention, it is preferable that one member of the k-th member and the (k+1)-th member comprises a plurality of first elements having a pinnacle shape; and the other member of the k-th member and the (k+1)-th member comprises a plurality of second elements having a shape that fits into the valley section between the plurality of first elements.

[0059] According to another aspect of the present invention, it is preferable that the pinnacle shape is a pyramid. According to another aspect of the present invention, it is preferable that the arrangement pitch of the plurality of first elements is less than or equal to ½ of the wavelength of the ultrasonic waves. According to another aspect of the present invention, it is preferable that the depth of the valley section at the plurality of hills and valleys is greater than or equal to ½ of the wavelength of the ultrasonic waves.

BRIEF DESCRIPTION OF THE DRAWING(s)

[0060] **FIG. 1** is a drawing for explaining the principle of an ultrasonic probe according to the present invention.

[0061] **FIG. 2** is a figure showing variation in piezoelectric constant in the thickness direction of the sonic speed control element shown in **FIG. 1**.

[0062] **FIG. 3** is a cross sectional view of the acoustic matching layer shown in **FIG. 1**.

[0063] **FIG. 4** is a top view of the acoustic matching layer shown in **FIG. 1**.

[0064] **FIG. 5** is a top view of a ultrasonic probe according to the present invention.

[0065] **FIG. 6** is a first cross sectional view of the ultrasonic probe according to the present invention.

[0066] **FIG. 7** is a second cross sectional view of the ultrasonic probe according to the present invention.

[0067] **FIG. 8** is a flowchart showing an example method for manufacturing a sonic speed control element according to the present invention.

[0068] **FIG. 9** is a drawing for explaining a partial polarization vanishing process for a piezoelectric material.

[0069] **FIG. 10** is a cross sectional view of another ultrasonic probe according to the present invention.

[0070] **FIG. 11** is a perspective view of the ultrasonic probe shown in **FIG. 10**.

[0071] **FIG. 12** is a schematic view showing the function of the acoustic matching layer shown in **FIG. 10**.

[0072] **FIG. 13** is a flowchart showing an example method for manufacturing the acoustic matching layer shown in **FIG. 10**.

[0073] **FIG. 14** is a cross sectional view showing an acoustic matching layer comprising a plurality of members (sub-layers).

[0074] **FIG. 15** is a cross sectional view of a conventional ultrasonic probe.

DESCRIPTION OF PREFERRED EMBODIMENTS

[0075] The preferred embodiments of the present invention will now be described with reference to the drawings.

[0076] **FIG. 1** shows the principle of an ultrasonic probe according to the present invention. An ultrasonic probe in

this embodiment comprises an array transducer as shown in **FIG. 7**. **FIG. 1** shows one of the transducer elements **10** of the array transducer along with other structures. **FIG. 1**(B) is a cross sectional view of a portion of the ultrasonic probe, **FIG. 1**(A) shows the variation in the specific acoustic impedance along the direction of travel of the ultrasonic waves (thickness direction), and **FIG. 1**(C) shows a plurality of electrical circuits.

[**0077**] As shown in **FIG. 1**(B), the transducer element **10** is for transmitting/receiving ultrasonic waves. The transducer element **10** is made of, for example, a PZT or composite piezoelectric material. At the side of the transducer element **10** away from the living body, a backing layer **12** is abutted with a signal lead **14** in between. The backing layer **12** is a known member for absorbing unnecessary ultrasonic waves radiated from the transducer element **10** to the rear side.

[**0078**] At the side of the transducer element **10** near the living body, a sonic speed control element **50** is abutted with a ground lead **16** in between. As described above, the sonic speed control element **50** is a member for controlling the sonic speed of the ultrasonic waves traveling therethrough. An impedance controller **38**, which will be described below, is connected to the sonic speed control element **50**, and the sonic speed control element **50** and the impedance controller **38** form a closed circuit. When the internal electrical impedance of the impedance controller **38** is varied, the acoustic characteristic of the sonic speed control element **50** is also varied. That is, the sonic speed of the ultrasonic waves traveling therethrough is changed. In this manner, the ultrasonic waves can be acoustically delayed. This sonic speed control element **50** is disclosed in Japanese Patent Laid-Open Publication No. Hei 11-123188. In this embodiment, the sonic speed control element **50** is made of a material similar to that for the transducer element **10**, for example, a PZT or composite piezoelectric material.

[**0079**] When the degree of the sonic speed control (amount of delay) of the sonic speed control element **50** is varied, the specific acoustic impedance of the sonic speed control element **50** is changed. In the sonic speed control element **50** of this embodiment, the piezoelectric constant is set to gradually decrease from the center portion (middle portion) to the end near the living body. As a result, the sonic speed control function in the sonic speed control element **50** decreases from the center portion towards the end near the living body. The piezoelectric constant at the end near the living body is substantially zero. Therefore, even when the sonic speed control is performed, the specific acoustic impedance at the end near the living body is always maintained at a constant value. In other words, as indicated by reference numerals **54**, **56** and **30**, the specific acoustic impedance is significantly varied in the vertical direction at the region from the end away from the living body to the center portion of the sonic speed control element **50** depending on the magnitude of the degree of sonic speed control, but in the region from the center portion to the end near the living body, the variation in the specific acoustic impedance decreases as the distance to the living body decreases (to a constant specific acoustic impedance value at the portion closest to the living body). This is because the piezoelectric constant is continuously reduced from the center portion towards the end near the living body, as described above. Because the specific acoustic impedance at the end of the sonic speed control element **50** near the living body is always constant, by setting the specific acoustic impedance at the end of the sonic speed control element **50** near the living body substantially equal to the specific acoustic impedance of the acoustic matching layer **52**, a step in the specific acoustic impedance at the boundary between the sonic speed control element **50** and the acoustic matching layer **52** can always be prevented. In other words, the reflections of ultrasonic waves produced at the boundary can be efficiently inhibited regardless of the operational state of the sonic speed control element **50**.

[**0080**] Even if the sonic speed control element **50** and the transducer element **10** are made of the same material, in the structure of **FIG. 1**, because the specific acoustic impedance at the end of the sonic speed control element **50** away from the living body changes, it is not possible to completely prevent the reflection of the ultrasonic waves at the boundary between the sonic speed control element **50** and the transducer element **10**. To this end, it is possible to continuously decrease the piezoelectric constant from the center portion of the sonic speed control element **50** to the end away from the living body. In this case, the piezoelectric constant at the end away from the living body may be set at zero.

[**0081**] In this embodiment, the piezoelectric constant is varied continuously in the sonic speed control element **50** from the center portion towards the end near the living body, in the thickness direction, but it is also possible to continuously vary the piezoelectric constant over the entire sonic speed control element **50** in the thickness direction, that is, from the end away from the living body to the end near the living body. Further, it is also possible to step-wise vary the piezoelectric constant instead of continuous variation.

[**0082**] As shown in **FIG. 1**(B), an acoustic matching layer **52** is provided at the side of the sonic speed control element **50** near the living body with a sonic speed control lead **20** in between. The acoustic matching layer **52** is a member for matching the specific acoustic impedance between the sonic speed control element **50** and the living body **26**. In the embodiment, the acoustic matching layer **52** has an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance is continuously changed along the thickness direction. More specifically, the specific acoustic impedance of the acoustic matching layer **52** at the end away from the living body is substantially equal to the specific acoustic impedance of the sonic speed control element **50** at the end near the living body and the specific acoustic impedance of the acoustic matching layer **52** at the end near the living body is substantially equal to the specific acoustic impedance of the living body **26**. Therefore, because both the sonic speed control element **50** and the acoustic matching layer **52** have an inclined characteristic in the specific acoustic impedance, it is possible to efficiently propagate the ultrasonic waves transmitted from the transducer element **10** to the living body **26**, with as much removal as possible of unnecessary internal reflections. Similarly, it is possible to efficiently propagate the ultrasonic waves coming back from the living body **26** to the transducer element **10** with as much removal as possible of unnecessary internal reflections. Thus, it is possible to solve the problem of waveform collapse of the ultrasonic waves or the like, and thereby, improve the quality of ultrasonic images.

[0083] The ground lead **16** and the sonic speed control lead **20** are constructed from, for example, a metal such as copper. Thus, theoretically, a large step is present in the specific acoustic impedance at the lead. However, by thinning the lead so that the thickness of the lead can be substantially ignored compared to the wavelength of the ultrasonic waves, in practice, the step in the specific acoustic impedance does not pose any significant problem.

[0084] In the structure shown in **FIG. 1**, only one acoustic matching layer is used. It is also possible to use two overlapped acoustic matching layers and set one or both layers to have the above inclined characteristic in the specific acoustic impedance. Also, in **FIG. 1**, no acoustic lens is provided, but it is possible, as necessary, to provide an acoustic lens at the side of the acoustic matching layer **52** near the living body.

[0085] Thin electrode layers which is not shown are formed respectively on one surface and the other surface of the transducer element **10**. The signal lead **14** and ground lead **16** are respectively connected to the electrode layers. A transmitter-receiver **36** is connected between the leads **14** and **16**. Transmission signals are supplied from the transmitter-receiver **36** to the transducer element **10**. Similarly, the received signal produced when an ultrasonic wave is received at the piezoelectric element **10** is output to the transmitter-receiver **36**.

[0086] Similar to the transducer element **10** as described above, thin electrode layers are formed respectively on one surface and the other surface of the sonic speed control element **50**. The ground lead **16** and sonic speed control lead **20** are respectively connected to the electrode layers. An impedance controller **38** is connected between the leads **16** and **20**. As described above, the impedance controller **38** controls the acoustic characteristic of the sonic speed control element **50** by varying the electrical impedance of the impedance controller **38**. More specifically, a variation of the electrical impedance of the impedance controller **38** causes variation in the amount of sonic speed control in the sonic speed control element **50**.

[0087] In the embodiment, as shown in **FIG. 1**(B), the ground lead **16** functions as the common ground, thereby, allowing reduction in the number of signal lines extending outside.

[0088] **FIG. 2** is a graph showing variation in the piezoelectric constant along the thickness direction of the sonic speed control element **50**. The piezoelectric constant at the end near the transducer element, that is, the end away from the living body, is a predetermined value K. In the thickness direction, the piezoelectric constant gradually decreases from the center portion towards the end near the acoustic matching layer **52**, that is, the end near the living body, ultimately to zero at the end surface near the living body. A method for setting such inclined characteristic in piezoelectric constant will be described later referring to **FIGS. 8 and 9**.

[0089] **FIGS. 3 and 4** show an example of the acoustic matching layer **52** shown in **FIG. 1**. **FIG. 3** is a vertical cross section of the acoustic matching layer and **FIG. 4** is a view of the acoustic matching layer seen from the living body. The position of the cross sectional view of **FIG. 3** is indicated by the A-A' line in **FIG. 4**. In the embodiment, the acoustic matching layer **52** is constructed from two members. More specifically, the acoustic matching layer **52** is constructed from a first member **60** and a second member **62**.

[0090] The first member **60** comprises a plurality of pyramid shaped elements having its vertex **60**A directed towards the living body. The pyramid shaped element is, for example, a pyramid having a quadrangle base. The second member **62** fills the gap. In this structure, one or a plurality of materials for the first member **60** is selected such that the specific acoustic impedance of the fist member **60** is equivalent to that of the sonic speed control element **50** at the end near the living body. In contrast, one or a plurality of materials for the second member **62** is selected such that the specific acoustic impedance of the second member **62** is equivalent to that of the living body. With such a structure, the end of the acoustic matching layer **52** away from the living body and the end of the sonic speed control element **50** near the living body are acoustically matched. At the same time, the end of the acoustic matching layer **52** near the living body and the living body are acoustically matched. Here, the first member **60** can be constructed from, for example, a PZT or a composite material, similar to the sonic speed control element **50**. The second member **62** can be constructed by mixing an additive such as silica powder, titanium oxide, etc., to a base material such as polyurethane, silicon rubber, etc. In this case, a desired specific acoustic impedance can be realized by adjusting the amount of additive to be added.

[0091] In order to manufacture an acoustic matching layer shown in **FIGS. 3 and 4**, a plurality of V-shaped channels extending in the X direction and a plurality of V-shaped channels extending in the Y direction are formed on a first material having a plate-like shape. The V-shaped channel may be formed by first tilting the first material with respect to a dicing saw, cutting the fist material in that state to form one inclined surface, tilting the first material in the other direction with respect to the dicing saw, and cutting the first material to form the other inclined surface. After a plurality of pyramid-shaped elements are formed through such a machining process, the second material in the liquid phase is poured into the gaps. The first material onto which the second material is poured is then left in vacuum to remove bubbles in the second material. The structure is then naturally left under normal temperature, normal humidity, and normal pressure, to cure the second material. Alternatively, any other formation method can be used for forming the plurality of pyramid-shaped elements, in place of the cutting process. The arrangement pitch of the plurality of pyramid-shaped elements is preferable as small as possible compared to the wavelength (λ) of the ultrasonic waves, and can be, for example, about $\lambda/5$.

[0092] **FIGS. 5, 6**, and **7** show an ultrasonic probe according to the embodiment. **FIG. 5** is a top view, **FIG. 6** is a first cross sectional view, and **FIG. 7** is a second cross sectional view, respectively of an ultrasonic probe.

[0093] The ultrasonic probe comprises a plurality of transducer elements **10** arranged in the Y direction (electronic scan direction), a plurality of sonic speed control elements **50** which are two-dimensionally arranged, a plurality of acoustic matching layers **52** which are two-dimensionally arranged, and a backing layer **12**. Each transducer element

10 has a plate-like shape extending in the elevation direction (X direction). Here, a signal lead **14** is provided for each transducer element **10** between each of the transducer elements **10** and the backing layer **12**. Further, a ground lead **16** is provided for each transducer element **10** between each of the transducer elements **10** and each of the sonic speed control elements **50**. The signal leads **14** and the ground leads **16** extend in the X direction. The plurality of signal leads **14** are aligned in the Y direction and the plurality of ground leads **16** are also aligned in the Y direction.

[**0094**] For each piezoelectric element **10**, a plurality of sonic speed control elements **50** is provided along the X direction. For each of the sonic speed control elements **50**, an acoustic matching layer **52** is provided. A plurality of sonic speed control leads **20** is provided between the plurality of sonic speed control elements **50** and the plurality of acoustic matching layers **52**. More specifically, a sonic speed control lead **20** is provided for a column formed from a plurality of sonic speed control elements **50** aligned in the Y direction.

[**0095**] In the above structure, a gap for preventing propagation of ultrasonic waves is present respectively between each of the plurality of transducer elements **10**, between each of the plurality of sonic speed control elements **50**, and between each of the plurality of acoustic matching layers **52**. In other words, cross-talk is prevented by these gaps. It is also possible to inject a filler which functions as an acoustic shield into these gaps.

[**0096**] Both the sonic speed control elements **50** and the acoustic matching layers **52** have the inclined characteristic in the specific acoustic impedance as described referring to **FIG. 1**. Because of this, it is possible to inhibit unnecessary reflections of the ultrasonic waves within the ultrasonic probe and improve the propagation efficiency of the ultrasonic waves.

[**0097**] In the embodiment shown in **FIGS. 5, 6**, and **7**, N piezoelectric elements **10** are provided along the Y direction. Also, M sonic speed control elements **50** are provided for each transducer element **10**. In other words, a total of N×M sonic speed control elements **50** and corresponding N×M acoustic matching layers **52** are provided. With such a structure, ultrasonic beams can be scanned along the Y direction, that is, the array direction, and, at the same time, along the X direction. In a conventional 2-D array transducer, for example, N×M signal lines are necessary, but in the ultrasonic probe of the embodiment, for example, only N signal lines are necessary.

[**0098**] **FIG. 8** is a flowchart showing a method for manufacturing a sonic speed control element **50** shown in **FIG. 1**. First, at step **S101**, a piezoelectric plate is prepared and machined into a predetermined size. Then, a lapping process is applied to one surface and the other surface of the piezoelectric plate in order to improve the flatness of each surface of the piezoelectric plate and thereby secure thickness precision.

[**0099**] Next, at step **S102**, an electrode layer is formed respectively on one surface and the other surface of the piezoelectric plate. In this case, a nickel chrome layer having a thickness of approximately 0.1 μm is formed as a base layer on each surface through sputtering or the like. Then, a metal layer having a thickness of approximately 0.5 μm is formed on the nickel chrome layer through sputtering.

[**0100**] At step **S103**, polarization process is applied. More specifically, a direct current high voltage is applied to the piezoelectric plate. When a PZT or the like which has a low Curie temperature of, for example, 150° C. is used as a material forming the piezoelectric plate, a direct current voltage of about 1500 V is applied per 1 mm of thickness. The application time is, for example, about 5 minutes. Then, in order to stabilize the polarization state in the piezoelectric plate, the piezoelectric plate is left, for example, for 3 days under normal temperature, normal humidity, and normal pressure (step **S104**).

[**0101**] Then, at step **S105**, a special treatment is applied for forming the inclined characteristic in the piezoelectric constant as described above. More specifically, as shown in **FIG. 9, a** cooling medium **64** is contacted to the electrode layer **70** formed on one surface of the piezoelectric plate **68**. On the other hand, a heating medium **66** is contacted to the electrode layer **72** formed on the other surface of the piezoelectric plate **68**. In this state, both heating and cooling processes are simultaneously applied. As the cooling medium **64**, a copperplate material having cooling water circulating inside can be used. As a heating medium **66**, a copperplate material having a built-in heater can be used. The heating temperature is set above the Curie temperature of the material forming the piezoelectric plate. The slope of the polarizability can be controlled by the heating duration and temperature. The polarity to which the inclined characteristic is to be added can be either the positive polarity or the negative polarity. According to this method, the polarization at the end of the piezoelectric plate **68** near the heating medium can be to disappear without eliminating the polarization at the end of the piezoelectric plate **68** near the cooling medium. That is, through such process, it is possible to gradually decrease the piezoelectric constant from positions near the cooling medium toward the heating medium, to eventually a piezoelectric constant of zero at the end near the heating medium. In other words, a sonic speed control element having the inclined characteristic in the piezoelectric constant can be manufactured.

[**0102**] As an alternative, after the above process, the orientation of the piezoelectric plate **68** can be inverted to allow contact of the cooling medium **64** with the electrode layer **72** and contact of the heating medium **66** with the electrode layer **70**, and the heating and cooling processes similar to the above can be applied. In this manner, a sonic speed control element having a mountain-shaped or bell-shaped inclined characteristic in the piezoelectric constant can be manufactured in which the piezoelectric constant is gradually decreased from the center portion toward both ends, to eventually a value of zero at the ends.

[**0103**] After step **S105** is completed, vertical and horizontal cutting processes are performed on the piezoelectric body (sonic speed control element) **68** as necessary. Other components are combined to the processed piezoelectric body. Ultimately, an ultrasonic probe as shown in **FIGS. 5, 6**, and **7** is constructed.

[**0104**] In the above embodiment, a partial polarization elimination process is applied after the polarization process. It is also possible to obtain the above inclined characteristic in the piezoelectric constant by, for example, mixing a non-piezoelectric material having a high dielectric constant into the piezoelectric material with the mixing ratio continuously varied along the thickness direction.

[0105] Referring to **FIGS. 10 through 14**, the conditions for allowing the acoustic matching layer having the inclined characteristic in the piezoelectric constant to effectively function will now be discussed.

[0106] **FIGS. 10 and 11** show another embodiment of an ultrasonic probe. **FIG. 10** is a schematic cross sectional view of an ultrasonic probe and **FIG. 11** is a perspective view of the ultrasonic probe. In these drawings, signal leads **14**, ground leads **16**, sonic speed control leads **20**, etc. are not shown.

[0107] The ultrasonic probe comprises a plurality of acoustic matching layers **130** which are two-dimensionally arranged, a plurality of sonic speed control elements **133** which are two-dimensionally arranged, a plurality of transducer elements **132** which are one-dimensionally arranged, and a backing layer **134**. Each of the members is layered in the Z direction. Each of the transducer elements **132** comprises a piezoelectric plate and electrode layers formed respectively on the upper surface and the lower surface of the piezoelectric plate. The backing layer **134** is for absorbing unnecessary ultrasonic waves radiated from the transducer elements **132** towards the back surface. Each of the acoustic matching layers **130** is respectively provided between the living body and each of the sonic speed control elements **133**, to acoustically match the living body and the sonic speed control elements **133**.

[0108] Each of the sonic speed control elements **133** has a function to adjust the sonic speed of the ultrasonic waves traveling therethrough. Each of the sonic speed control elements **133** may have either the inclined characteristic in the specific acoustic impedance as described above or a uniform characteristic (non-inclined characteristic) in the specific acoustic impedance.

[0109] As shown in **FIG. 11**, the plurality of transducer elements **132** is aligned in the Y direction. In other words, the plurality of transducer elements **132** constitutes a 1-D array transducer. For each transducer element **132**, a plurality of sonic speed control elements **133** is provided which are aligned along the X direction. The structure shown in **FIG. 11** is similar to the structure shown in **FIG. 4**.

[0110] For the plurality of transducer elements **132**, a cut-in channel **140** is formed between adjacent transducer elements **132**. These cut-in channels **140** extend in the X direction and are formed using a dicing saw or the like. Similarly, a cut-in channel is formed between the adjacent sonic speed control elements **133** and between adjacent acoustic matching layers **130** using a dicing saw or the like. These cut-in channels extend in the X direction and in the Y direction.

[0111] In the embodiment, the acoustic matching layer **130** comprises a first member **150** and a second member **152** which have differing specific acoustic impedances and overlap in the Z direction. The first member **150** is constructed from a material having a specific acoustic impedance Z_1 which is similar to that of the sonic speed control element **133**. The first member **150** comprises a plurality of first elements **154** having a pinnacle shape with the top edge directed toward the living body (Z direction). One or a plurality of first elements **154** is formed for each of the acoustic matching layers **130**, the number of which is determined by conditions that will be described below. In general, a plurality of first elements **154** is formed for each of the acoustic matching layers **130**. The plurality of first elements **154** is connected to each other at their lower sections. On the other hand, a second member **152** is constructed from a material having a specific acoustic impedance Z_2 similar to the living body. The second member comprises a second element **155** having a shape that fits the gaps formed between the plurality of first elements **154** and at both ends of the first member **150**. In any case, the first member **150** comprises at least one first element **154** which projects toward the living body (upper side) and the second member **152** comprises at least one second element **155** which projects away from the living body (lower side). Because the upper surface of the first member **150** and the lower surface of the second member **152** are completely contacted with each other, there is no layer of air at the boundary surface. With the alternate arrangement of the plurality of first elements **154** and the plurality of second elements **155**, the specific acoustic impedance within the acoustic matching layer **130** is continuously varied along the direction of travel of the ultrasonic waves (Z direction). In other words, the acoustic matching layer **130** has an inclined characteristic in the specific acoustic impedance.

[0112] **FIG. 12** is an enlarging schematic view of the acoustic matching layer **130** shown in **FIG. 10**. The first element **154** has a "Λ" shape (wedge shape) in which the vertical cross section seen from the Y direction (refer to **FIG. 11**) is an isosceles triangle. The vertical cross section of the first element **154** seen from the X direction has a rectangular shape. The vertical cross section of the second element **155** seen from the Y direction (refer to **FIG. 11**) is an isosceles triangle. The vertical cross section of the second element **155** seen from the X direction is a rectangle. The shapes of the elements **154** and **155**, however, are not limited to the ones shown in these figures.

[0113] The boundary **156** between the first member **150** and the second member **152** is formed as two types of alternately connected surface elements having different orientation. The angle between each of the surface elements and the normal with respect to the surface of the acoustic matching layer **130** (Z direction) is θ. The angle θ is determined by conditions which will be described later.

[0114] The transmitted ultrasonic waves propagating from the transducer element via the sonic speed control element primarily propagate in the direction of the normal. In **FIG. 12**, an arrow **160** represents the direction of the transmitted ultrasonic waves. The transmitted ultrasonic waves propagate in the first member **150** in the direction of the normal. The received ultrasonic waves coming from the living body are primarily incident perpendicular to the surface of the acoustic matching layer **130** and propagates in the direction of the normal. In **FIG. 12**, an arrow **162** represents the direction of the received ultrasonic waves in the second member **152**.

[0115] Here, the sonic speed of the ultrasonic waves within the first member **150** is defined as C_1. Similarly, the sonic speed of the ultrasonic waves within the second member **152** is defined as C_2. When the sonic speed C_1 is equal to the sonic speed C_2 (C_1=C_2), total internal reflection is not generated at the boundary **156** for either the transmitted ultrasonic waves or the received ultrasonic waves. However, in general, because the first member **150** and the

second member **152** are formed from different materials, there is some difference in the sonic speeds C_1 and C_2.

[**0116**] The behaviors of the transmitted ultrasonic waves and of the received ultrasonic waves within the acoustic matching layer **130** will now be described for a case where $C_1>C_2$. For the case where $C_1<C_2$, the behaviors of the transmitted ultrasonic waves and of the received ultrasonic waves will merely be inverted compared to the case of $C_1>C_2$, and thus, will not described.

[**0117**] The behavior of the transmitted ultrasonic waves within the acoustic matching layer **130** is first described. In the acoustic matching layer **130**, the transmitted ultrasonic waves **160** incident perpendicularly from the surface near the sonic speed control element **133** is incident on the boundary **156** with an angle θ, and is refracted in the direction of an arrow **170**. The angle θ_2 between the arrow **170** and the boundary **156** can be obtained from Snell's law as follows.

$$\cos\theta_2/\cos\theta=C_2/C_1 \quad \text{(Equation 3)}$$

[**0118**] Because the transmitted ultrasonic waves is incident from the first member **150** having a larger sonic speed C_1 to the second member **152** having a smaller sonic speed C_2, no total internal reflection is generated at the boundary **156**.

[**0119**] Next, the behaviors of the received ultrasonic waves in the acoustic matching layer **130** will be described. In the acoustic matching layer **130**, the received ultrasonic waves incident perpendicularly from the surface near the living body (arrow **162**) is incident on the boundary with an angle θ, and is refracted in the direction of an arrow **172**. The angle θ_1 between the arrow **172** and the boundary **156** can be obtained from Snell's law as follows.

$$\cos\theta_1/\cos\theta=C_1/C_2 \quad \text{(Equation 4)}$$

[**0120**] The slope angle θ of the boundary **156** is set to satisfy the following equation.

$$C_1<C_2/\cos\theta \quad \text{(Equation 5)}$$

[**0121**] When the slope angle θ of the boundary **156** is set so that it satisfies the above equation, a relationship, $\theta_1>0$, can be deduced from equation (4), which means that no total internal reflection is generated at the boundary for the received ultrasonic waves that is incident vertically on the acoustic matching layer **130**.

[**0122**] The above equation (5) sets the lower limit for θ. The lower limit is determined by the ratio between C_1 and C_2. That is, as the value of C_2/C_1 approaches 1, the lower limit of θ approaches 0.

[**0123**] When θ is determined in reality, a few other points must be considered. In order to form a plurality of first elements having a pinnacle shape to realize quasi-inclination of the specific acoustic impedance, a condition, $\theta<90°$, must be satisfied, because when $\theta=90°$, the boundary **156** becomes flat. As θ becomes larger, the arrangement pitch of the plurality of first elements **154** becomes larger, resulting in reduction in the effect of the quasi-inclination of the specific acoustic impedance. Therefore, in order to desirably realize the inclination of the specific acoustic impedance by the plurality of first elements **154**, the arrangement pitch for the plurality of the first elements **154** is preferably as small as possible. For example, it is preferable to set the arrangement pitch for the plurality of first elements **154** to be less than or equal to ½ of the wavelength of the ultrasonic waves. It is also preferable to set the height of each of the first elements **154** to greater than or equal to ½ of the wavelength of the ultrasonic waves. Considering these points, it is preferable that θ is as small as possible.

[**0124**] On the other hand, received ultrasonic waves may be incident from a direction tilted from the normal with respect to the surface of the acoustic matching layer **130** (here, the incident angle of the ultrasonic waves with respect to the normal is defined as Δθ). In order to produce no total internal reflection at the boundary **156** and allow the received ultrasonic waves incident at a tilted angle to reach the sonic speed control element **133**, the lower limit of θ must be a value shifted up from the value defined by the equation (5). The increase in the lower limit of θ depends on the maximum value of Δθ at which the received ultrasonic waves can be received. As the maximum value of Δθ increases, the lower limit of θ also increases. Furthermore, in general, as the angle of the top edge of the first element **154** and of the second element **155** becomes more acute, the machining becomes more difficult. This machining constraint also sets a lower limit for θ. As described, for decreasing θ, there are a number of other constraints in addition to the condition set forth by the above equation (5).

[**0125**] It is preferable that the angle of slope θ be determined considering these various conditions.

[**0126**] The first member **150** is constructed by, for example, adding an additive material (filler) onto a base material. The base material is, for example, an epoxy resin. The filler is, for example, tungsten, tungsten carborundum, tungsten silicide, tantalum, or the like. The epoxy resin is a material having itself a low specific acoustic impedance of about 3 MRayl. A filler having a high specific acoustic impedance is added to the base material. In this manner, a specific acoustic impedance value which is similar to that of the piezoelectric material can be obtained. For example, a first member made by adding a large amount of tungsten powder to an epoxy resin has a specific acoustic impedance of 20 MRayl and a sonic speed C_1 of 1600 m/sec.

[**0127**] The second member **152** is constructed from, for example, a poly-ether-block-amido-copolymer, an epoxy resin to which silicone powder is added, a silicone rubber, a butadiene rubber, or the like. By using these materials, the specific acoustic impedance Z_2 of the second member **152** can be set to be about 1.6 MRayl which is very close to the specific acoustic impedance of the living body surface. Also, the above materials allow the sonic speed C_2 of the second member **152** to be approximately 1600 m/s which corresponds to the sonic speed C_1 of the first member **150**.

[**0128**] **FIG. 13** is a flowchart for explaining the manufacturing steps of the acoustic matching layer **130**. First, a base plate is formed as the original material for creating a first member **150**. More specifically, a mixture solution (first material) in which a filler such as tungsten-carborundum powder is mixed to a liquid-phase epoxy resin is used, and the mixture solution is poured into a mold (step **S200**). Within the mixture solution, air is present which is mixed during the addition of filler. To this end, the mixture solution poured into the mold is left under a normal temperature for de-bubbling, that is, to remove air (step **S205**). In order to promote de-bubbling, it is preferable to store the mixture solution inside a depressurized container. After de-bubbling,

the mixture solution is cured. More specifically, because an epoxy resin is a thermosetting resin, the mixture solution is introduced into a thermostat, and cured under a normal pressure, a normal humidity, and a high temperature such as, for example, 100° C., for 5 hours (step **S210**). Through this curing process, the base plate is completed.

[**0129**] A plurality of channels having a V-shape is then formed on the cured base plate. In this manner, a plurality of first elements **154** are formed. In this case, a dicing saw is placed tilted with respect to the base plate material and cutting is performed by the dicing saw along one tilted surface of the first element **154** having a Λ shape. Then, the slope of the dicing saw is changed and cutting is performed along the other tilted surface of the first element **154** (step **S215**). In this manner, a base plate (machined base plate) onto which a plurality of first elements are formed is completed. The machined base plate has a shape in which a plurality of first members are interconnected.

[**0130**] Next, the machined base plate is again surrounded by a mold. A liquid material (second material) for constituting the second member **152** is poured into the mold (step **S220**). Then, similar to step **S205**, a de-bubbling process is applied (step **S225**), in order to ensure that the poured material fills to the corners of the V-shaped channels between the plurality of first elements **154** and to remove the mixed air bubbles. After the de-bubbling process, the liquid material is cured similar to step **S210** (step **S230**). By the curing process, an acoustic matching plate corresponding to a plurality of linked acoustic matching layers is constructed. A machining process for the external shape is applied to the acoustic matching plate. More specifically, in order to secure flatness and parallelity between upper and lower surfaces of the acoustic matching plate, a grinding process is applied to these surfaces (step **S235**).

[**0131**] The coupling plate produced as above is abutted to the sonic speed control plate at the assembly step of the ultrasonic probe. For the combined structure of the acoustic matching plate and the sonic speed control plate, a cutting process is applied a plurality of times along the X direction and the Y direction using a dicing saw or the like. In this manner, a plurality of acoustic matching layers **130** and a plurality of sonic speed control elements **133** are separately formed.

[**0132**] In the above description, the acoustic matching layer is formed from two members (that is, a first member and a second member). It is also possible that the acoustic matching layer is formed from a larger number of members. However, it is preferable to construct the acoustic matching layer so that, in a plurality of members, the boundary between the adjacent members has a shape with a plurality of hills and valleys.

[**0133**] **FIG. 14** is a vertical cross sectional view schematically showing an acoustic matching layer **200** made of n members ($n \geqq 3$). The acoustic matching layer **200** comprises a first member **202**, a second member **204**, . . . , an (n−1)-th member **206**, and an n-th member **208**, all of which are layered from the side near the sonic speed control element towards the living body. A plurality of first elements **254** having a pinnacle shape with the top edge (or vertex) pointing towards the living body are formed on (the upper section of) each of the members other than the upper-most, n-th member **208**. In contrast, a plurality of second members **255** having a pinnacle shape with the top edge (or vertex) pointing towards the lower side are formed on (the lower section of) each of the members other than the lower-most, first member **202**. The plurality of second elements **255** fit with the plurality of first elements **254** in the valley between the plurality of the first elements **254**. In other words, between two adjacent members, the lower surface of the upper member and the upper surface of the lower member are completely abutted. The first member **202** is constructed from a material having a specific acoustic impedance Z_1 similar to that of the sonic speed control element. The n-th member **208** is constructed from a material having a specific acoustic impedance Z_n similar to that of the living body. The material for each of the members are selected so that the specific acoustic impedance of the members monotonically changes from Z_1 to Z_n. With the monotonic change in the specific acoustic impedance and the fact that the boundary between two adjacent sub-layers have a shape with hills and valleys, an acoustic matching layer **200** having essentially an inclined characteristic in the specific acoustic impedance can be realized.

[**0134**] The n members are constructed based on conditions similar to the conditions explained referring to **FIG. 12**. In the following description, the boundary between the k-th member and the (k−1)-th member (here, $1 \leqq k \leqq (n-1)$) is represented by a reference numeral **210**-k. At a boundary **210**-k, the conditions related to the slope angle of the boundary **210**-k for reducing the generation of total internal reflection of the ultrasonic are:

$$C_{k+1} < C_k < C_{k+1}/\cos\theta_k \quad \text{(Equation 6)}$$

[**0135**] or

$$C_k < C_{k+1} < C_k/\cos\theta_k \quad \text{(Equation 7)}$$

[**0136**] or

$$C_k = C_{k+1} \quad \text{(Equation 8)}$$

[**0137**] where C_k is the sonic speed of ultrasonic waves in the k-th member ($1 \leqq k \leqq n$), θ_k is the angle between the normal **212** with respect to the surface of the acoustic matching layer **200** and the boundary **210**-k.

[**0138**] If all of the boundaries **210**-k ($1 \leqq k \leqq (n-1)$) are formed to satisfy the above conditions, propagation of the transmitted ultrasonic waves and the received ultrasonic waves through the acoustic matching layer **200** can be improved.

[**0139**] In the above description, each of the acoustic matching layers **130** and **200** are individually separated. It is also possible to link the acoustic matching layers **130** and **200** in the X direction and/or Y direction. In order to reduce the cross-talk of ultrasonic waves, however, it is preferable that each of the acoustic matching layers **130** and **200** is individually separated.

[**0140**] In the above acoustic matching layers **130** and **200**, a plurality of first elements **154** and **254** and a plurality of second elements **155** and **255** are arranged in the elevation direction (X direction). It is also possible to set the plurality of first elements **154** and **254** and the plurality of second elements **155** and **255** to be arranged in the electronic scan direction (arrangement direction of the transducer elements).

[**0141**] The shape of the elements **154** and **254** may be a pyramid. In the above description, the surface elements forming the boundaries **156** and **210**-k are tilted planes and

the angles of tilt θ and θ_k are constant. However, the angle of tilt θ and θ_k may vary on the boundaries **156** and **210**-k as long as the equation (6), (7), or (8) is satisfied at all points on the boundaries **156** and **210**-k. In other words, the boundaries **156** and **210**-k maybe formed from curved surfaces.

What is claimed is:

1. An ultrasonic probe comprising:

a transducer element for transmitting and receiving ultrasonic waves;

a sonic speed control element provided at the side of said transducer element near a living body and through which said ultrasonic waves transmitted or received by said transducer element travel, said sonic speed control element having a function to control the sonic speed of said ultrasonic waves traveling therethrough and having an inclined characteristic in the sonic speed control effect in which the sonic speed control effect is gradually changed along the direction of travel of said ultrasonic waves over the whole sonic speed control element or in a portion of said sonic speed control element in said direction of travel; and

an acoustic matching layer provided at the side of said sonic speed control element near the living body.

2. An ultrasonic probe according to claim 1, wherein the specific acoustic impedance characteristic within said acoustic matching layer is set based on the specific acoustic impedance of said sonic speed control element at the end near a living body and the specific acoustic impedance of said living body.

3. An ultrasonic probe according to claim 1, wherein said sonic speed control effect of the sonic speed control element is gradually reduced from the side of said sonic speed control element away from the living body towards the end of the sonic speed control element near the living body; and

the specific acoustic impedance of said acoustic matching layer corresponds to the specific acoustic impedance of said end of the sonic speed control element near the living body.

4. An ultrasonic probe according to claim 1, wherein

said sonic speed control element is made of a piezoelectric material; and

the piezoelectric constant of said piezoelectric material changes along said direction of travel.

5. An ultrasonic probe according to claim 4, wherein said piezoelectric constant gradually decreases from the middle portion of said sonic speed control element towards said end of the sonic speed control element near the living body.

6. An ultrasonic probe according to claim 5, wherein said piezoelectric constant at said end of the sonic speed control element near the living body is zero.

7. An ultrasonic probe according to claim 4, wherein said piezoelectric constant gradually decreases from the middle portion of said sonic speed control element towards said end of the sonic speed control element near the living body and towards said end of the sonic speed control element away from the living body.

8. An ultrasonic probe according to claim 7, wherein said piezoelectric constants at said ends of the sonic speed control element near the living body and away from the living body are zero.

9. An ultrasonic probe according to claim 1, wherein said acoustic matching layer has an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance gradually changes from the end away from the living body toward the end near the living body.

10. An ultrasonic probe according to claim 9, wherein

said specific acoustic impedance of the end of said acoustic matching layer away from the living body agrees with the specific acoustic impedance of the end of said sonic speed control element near the living body; and

the specific acoustic impedance of the end of said acoustic matching layer near said living body agrees with the specific acoustic impedance of said living body.

11. An ultrasonic probe according to claim 10, wherein

said acoustic matching layer comprises a first member and a second member having different specific acoustic impedances; and

the compositional ratio between said first member and said second member changes along said direction of travel.

12. An ultrasonic probe according to claim 11, wherein

said first member has a specific acoustic impedance which is equal to the specific acoustic impedance of said end of the sonic speed control element near the living body; and

said second member has a specific acoustic impedance which is equal to the specific acoustic impedance of said living body.

13. An ultrasonic probe according to claim 12, wherein

said first member comprises a plurality of pyramid elements having a pinnacle shape projecting towards the living body; and

said second member is filled into the gap between said to plurality of pyramid elements.

14. An ultrasonic probe comprising:

N transducer elements for transmitting and receiving ultrasonic waves;

N×M sonic speed control elements provided at the ends of said N transducer elements near the living body and through which said ultrasonic waves travel, with M sonic speed control elements provided for each transducer element, each sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough and having an inclined characteristic in the sonic speed control effect in which the sonic speed control effect gradually changes along said direction of travel of the ultrasonic waves over the entire length of, or over a portion of, said direction of travel; and

N×M acoustic matching layers provided at the side of said N×M sonic speed control elements near the living body.

15. An ultrasonic probe comprising:

a transducer element for transmitting and receiving ultrasonic waves;

a sonic speed control element provided at the side of said transducer element near the living body and through which the ultrasonic waves travel, said sonic speed

control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough; and

an acoustic matching layer provided at the side of said sonic speed control element near the living body and having an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance monotonically changes along the direction of travel of the ultrasonic waves.

16. An ultrasonic probe according to claim 15, wherein said sonic speed control element has a non-inclined characteristic in the sonic speed control effect in which the sonic speed control effect is uniform at every position in said direction of travel.

17. An ultrasonic probe according to claim 15, wherein said sonic speed control element has an inclined characteristic in the sonic speed control effect in which the sonic speed control effect gradually changes along said direction of travel.

18. An ultrasonic probe according to claim 15, wherein

said acoustic matching layer comprises a first member and a second member overlapped in said direction of travel;

said first member and said second member have different specific acoustic impedances; and

the boundary between said first member and said second member has a shape with a plurality of hills and valleys.

19. An ultrasonic probe according to claim 18, wherein when the crossing angle between said direction of travel and said boundary is θ, the sonic speed of said ultrasonic waves within said first member is C_1, and the sonic speed of said ultrasonic waves within said second member is C_2, a condition,

$$C_2<C_1<C_2/\cos\theta$$

or a condition,

$$C_2=C_1$$

is satisfied.

20. An ultrasonic probe according to claim 19, wherein

one member, of said first member and said second member, provided near the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of the living body; and

the other member of said first member and said second member provided away from the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of said sonic speed control element.

21. An ultrasonic probe according to claim 20, wherein

one member of said first member and said second member comprises a plurality of first elements having a pinnacle shape; and

the other member of said first member and said second member comprises a plurality of second elements having a shape to fit in the valley section between said plurality of first elements.

22. An ultrasonic probe according to claim 21, wherein said pinnacle shape is a pyramid shape.

23. An ultrasonic probe according to claim 21, wherein the arrangement pitch of said plurality of first elements is less than or equal to ½ of the wavelength of said ultrasonic waves.

24. An ultrasonic probe according to claim 21, wherein the depth of said valley section is greater than or equal to ½ of the wavelength of said ultrasonic waves.

25. An ultrasonic probe, comprising:

a transducer element for transmitting and receiving ultrasonic waves;

a sonic speed control element provided at the side of said transducer element near the living body and through which the ultrasonic waves travel, said sonic speed control element having a function to control the sonic speed of the ultrasonic waves traveling therethrough; and

an acoustic matching layer provided at the side of said sonic speed control element near the living body and having an inclined characteristic in the specific acoustic impedance in which the specific acoustic impedance monotonically changes along said direction of travel, the acoustic matching layer made of n members (where n is an integer greater than or equal to 3) overlapped in said direction of travel, and the specific acoustic impedances of said n members changing in steps along said direction of travel.

26. An ultrasonic probe according to claim 25, wherein each of the boundaries between said n members has a shape with hills and valleys.

27. An ultrasonic probe according to claim 26, wherein when the crossing angle between said direction of travel and the boundary between the k-th member (where k is an integer satisfying the condition, $1\leqq k\leqq(n-1)$) and (k+1)-th member is θ_k, the sonic speed of the ultrasonic waves within the k-th member is C_k, and the sonic speed of the ultrasonic waves within the (k+1)-th member is C_{k+1}, a condition,

$$C_{k+1}<C_k<C_{k+1}/\cos\theta_k$$

or a condition,

$$C_{k+1}=C_k$$

is satisfied.

28. An ultrasonic probe according to claim 27, wherein

the member, among said n members, that is closest to the living body has a specific acoustic impedance corresponding to the specific acoustic impedance of said living body; and

the member, among said n members, that is closest to said sonic speed control element has a specific acoustic impedance corresponding to the specific acoustic impedance of said sonic speed control element.

29. An ultrasonic probe according to claim 27, wherein

one member of said k-th member and said (k+1)-th member comprises a plurality of first elements having a pinnacle shape; and

the other member of said k-th member and said (k+1)-th member comprises a plurality of second elements having a shape that fits into the valley section between said plurality of first elements having a pinnacle shape.

30. An ultrasonic probe according to claim 29, wherein said pinnacle shape is a pyramid.

31. An ultrasonic probe according to claim 29, wherein the arrangement pitch of said plurality of first elements is less than or equal to ½ of the wavelength of said ultrasonic waves.

32. An ultrasonic probe according to claim 26, wherein the depth of the valley section at said plurality of hills and valleys is greater than or equal to ½ of the wavelength of said ultrasonic waves.

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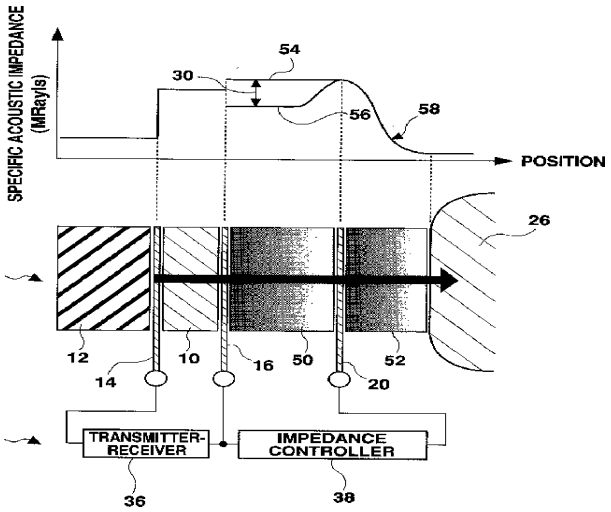
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