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(54) ULTRASONIC PROBE AND ULTRASONIC DIAGNOSTIC APPARATUS

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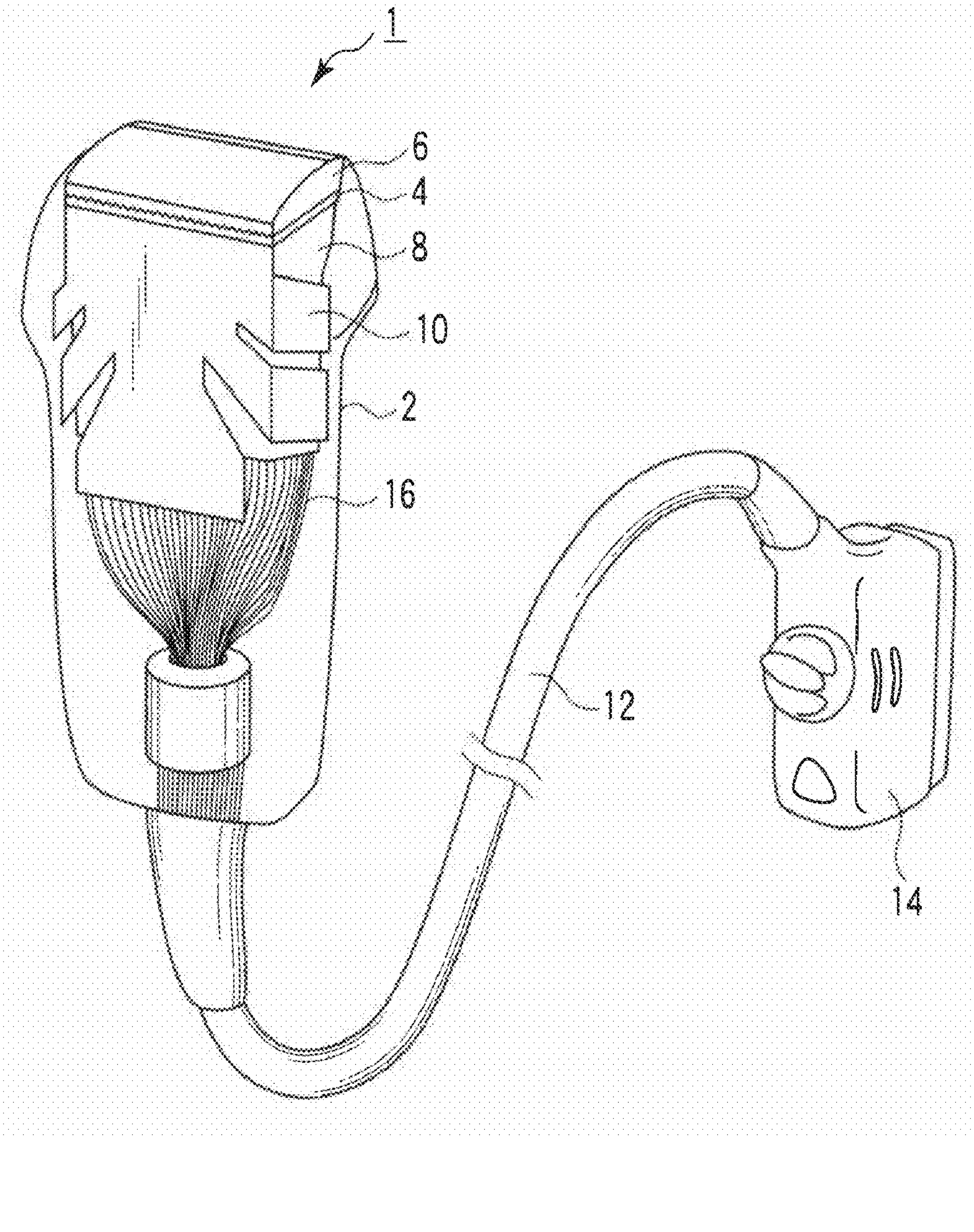
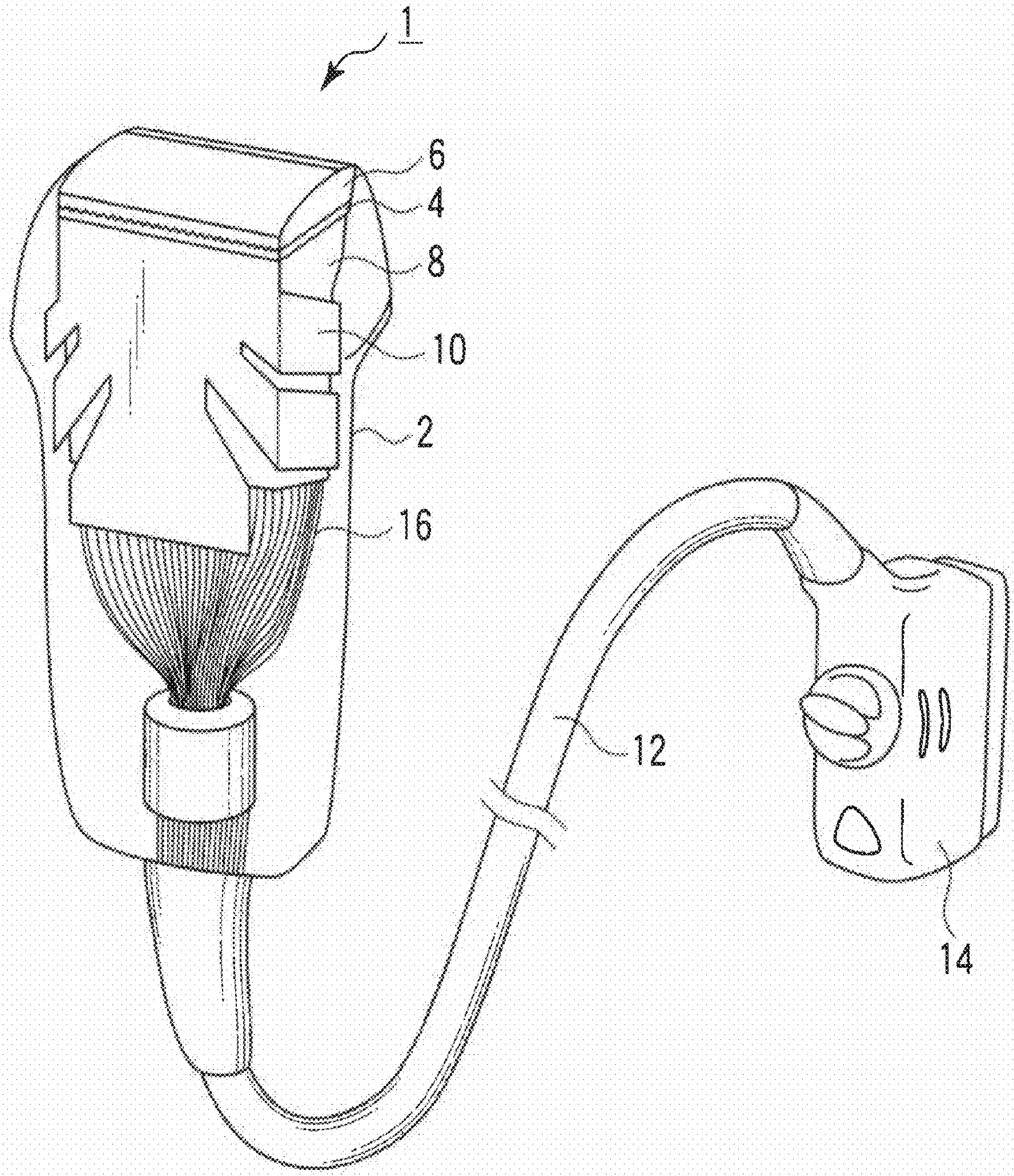
(52) **U.S. Cl.** **600/443**; 310/336; 600/459

(57) **ABSTRACT**

A base has a plurality of projections or recesses. Each of the projections or recesses corresponds to one channel of vibration elements. Each of the vibration elements has a plurality of MUT elements. Each of the MUT elements transmits and receives ultrasonic waves. A plurality of MUT elements are arranged in each of the projections or recesses. Consequently, each of the vibration elements can transmit and receive ultrasonic waves having radiation surfaces curved along the surfaces of the projections or recesses.





F I G. 1

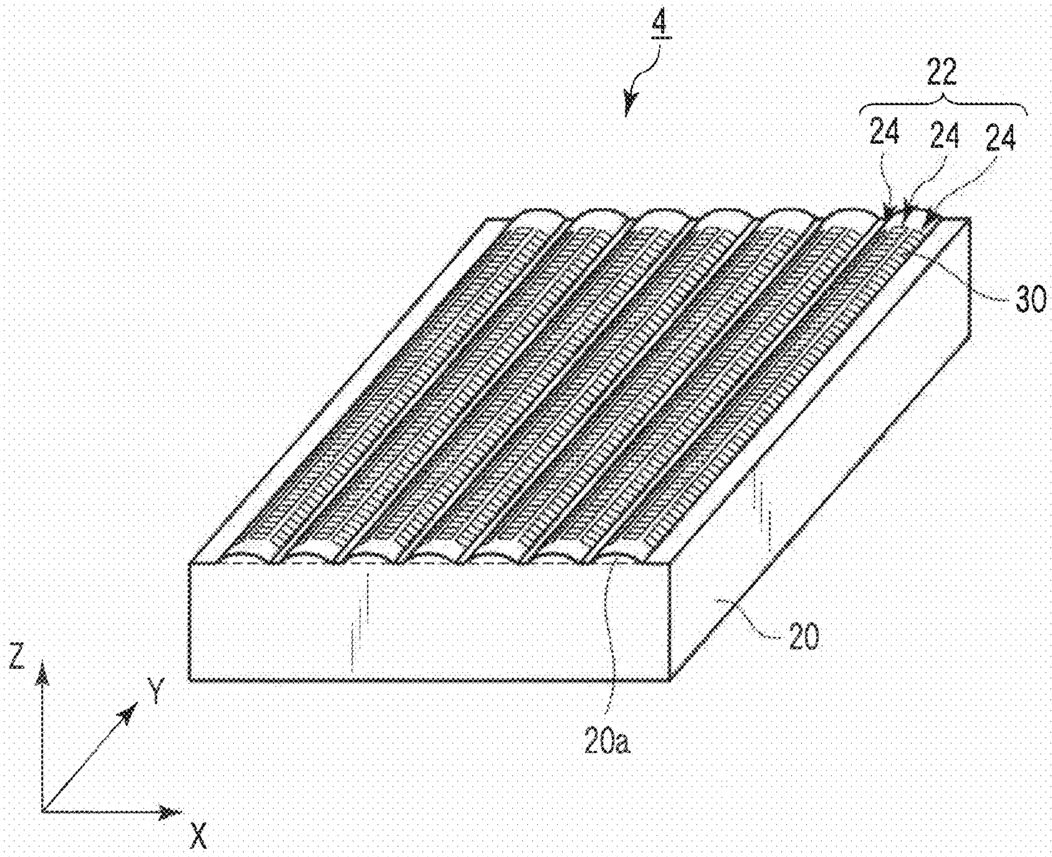


FIG. 2

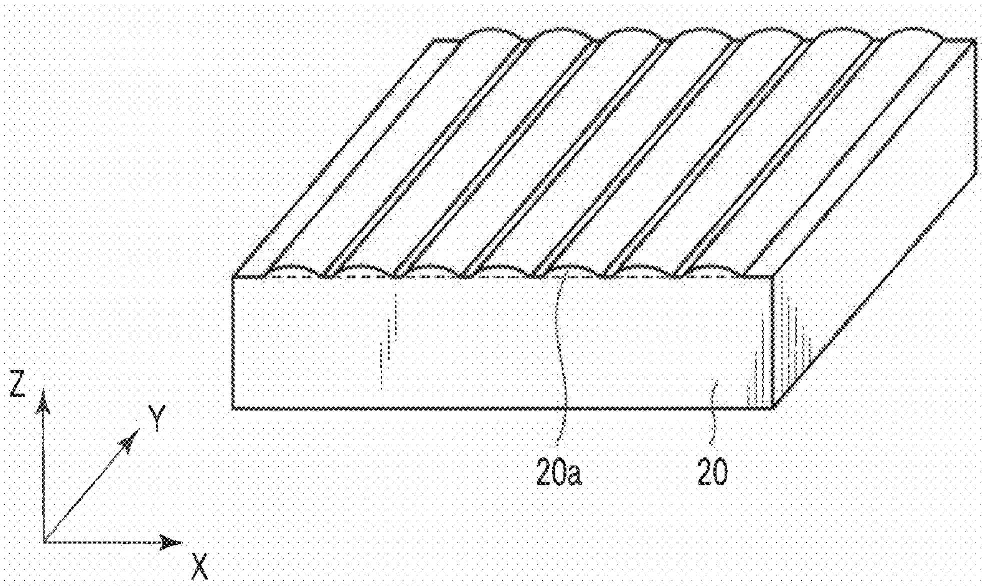
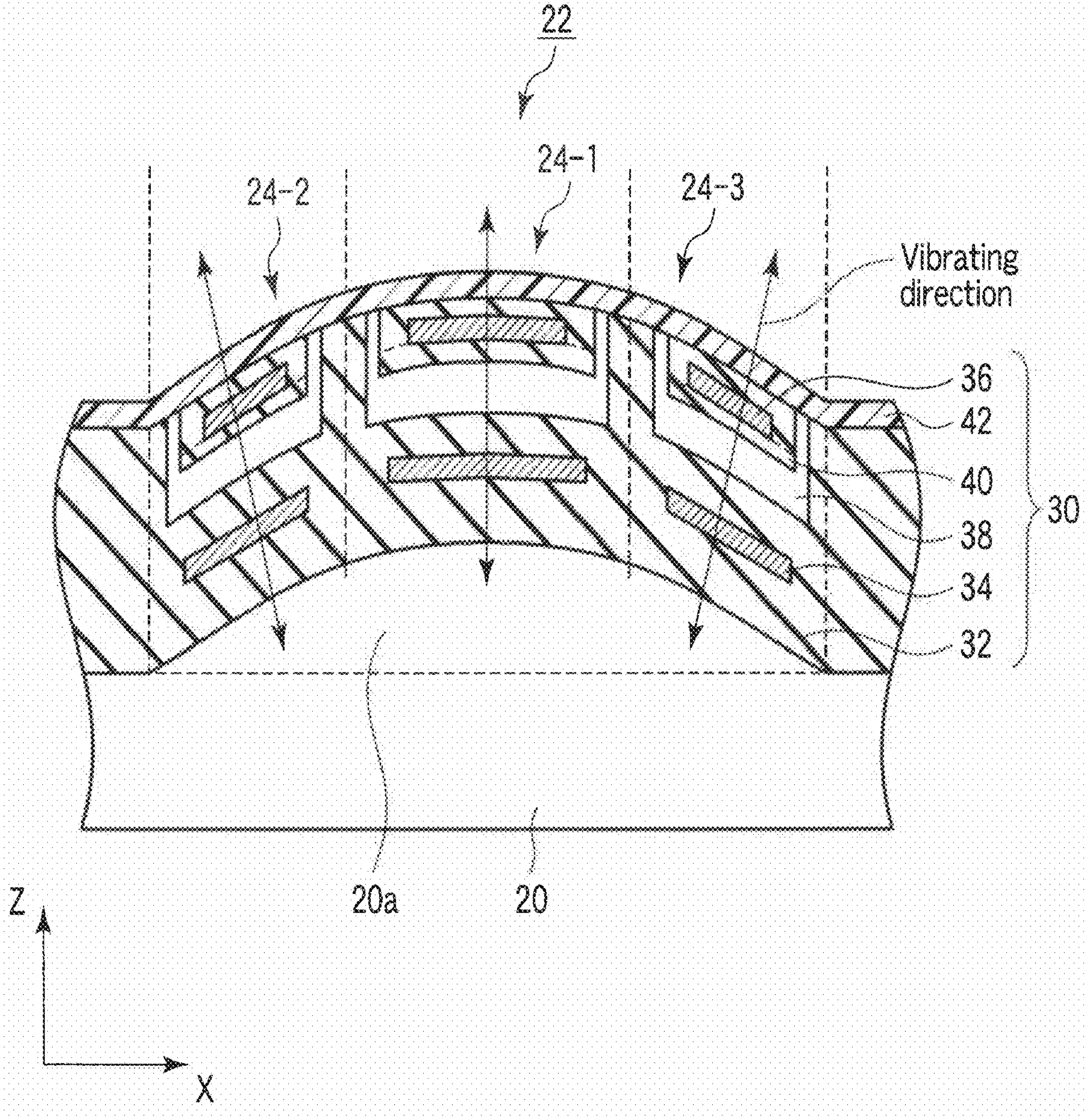


FIG. 3


22
24-2
24-1
24-3
Vibrating direction
36
42
40
30
38
34
32
20a
20
Z
X

F I G. 4

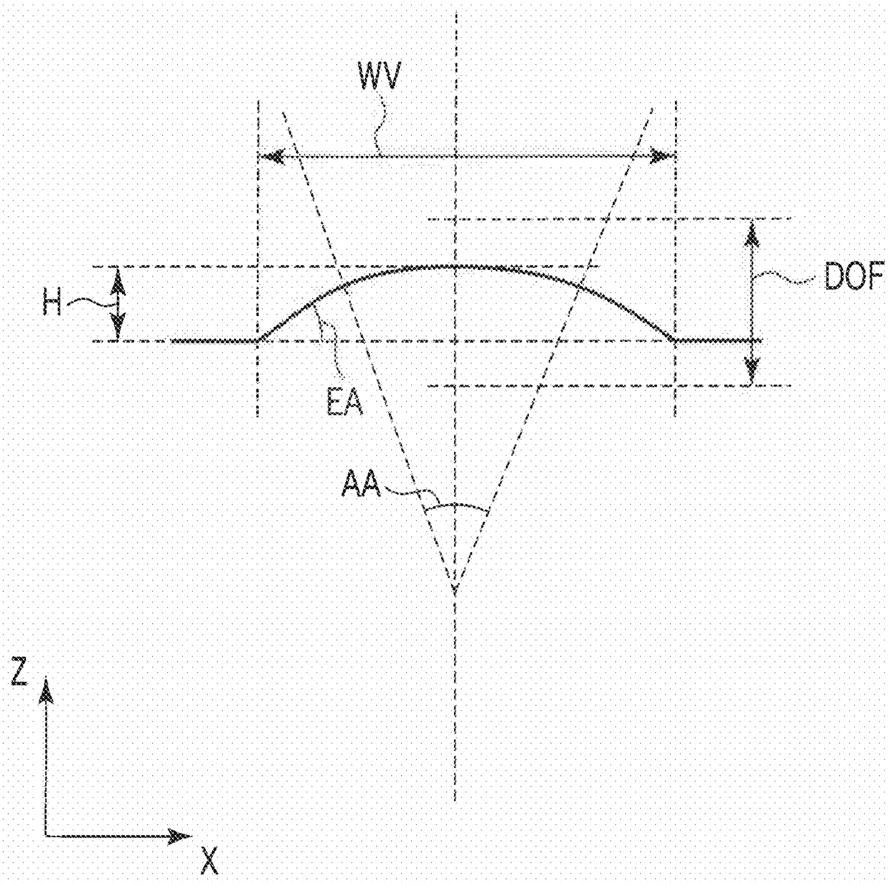


FIG. 5

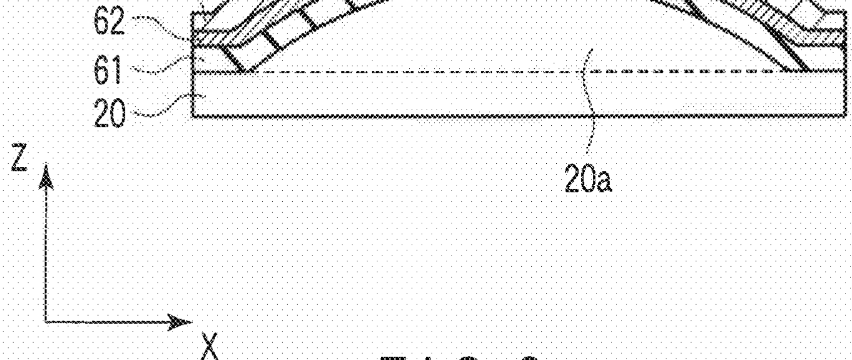
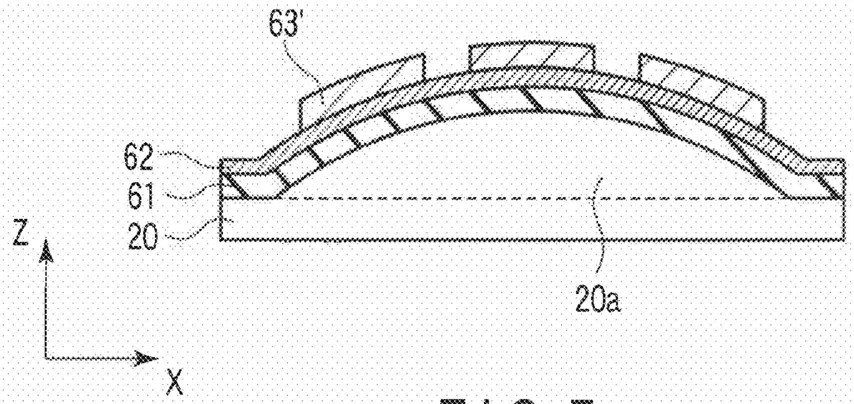
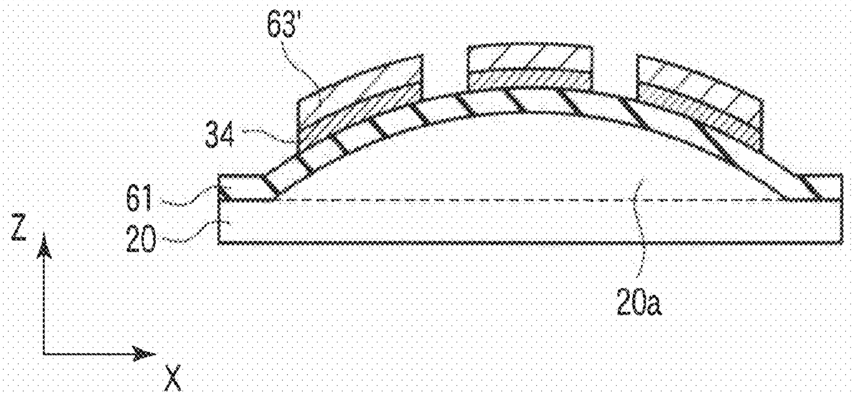


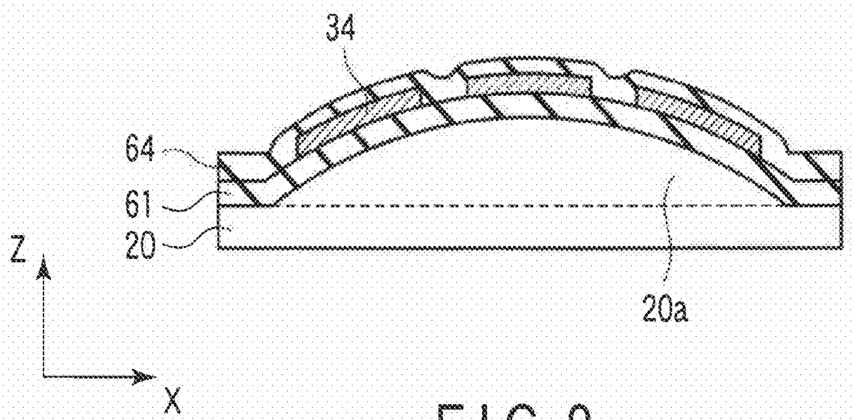
FIG. 6



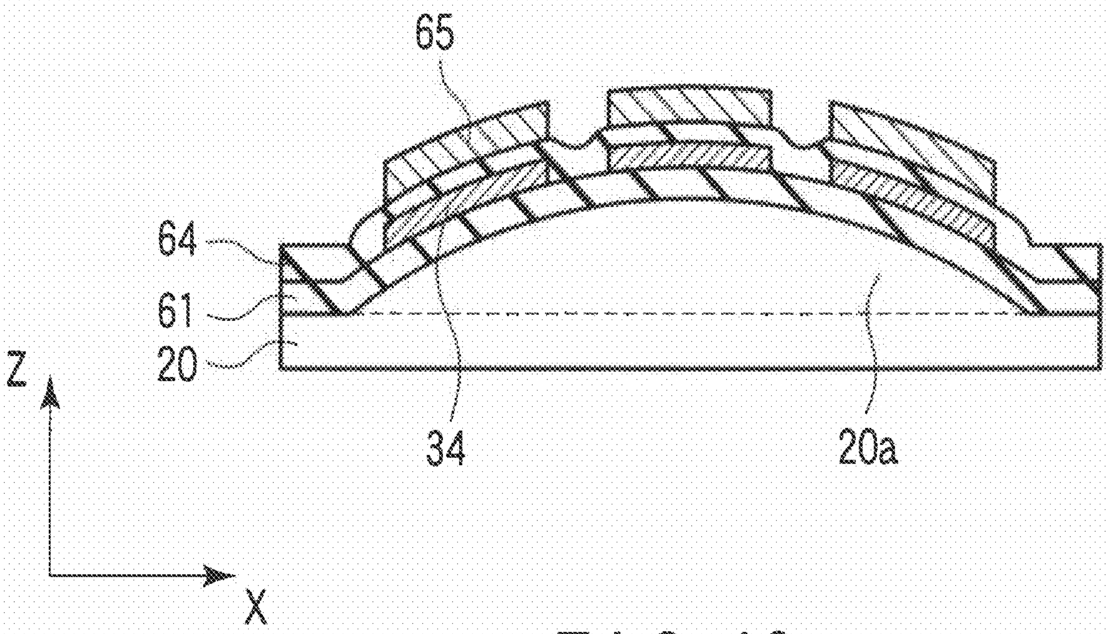
F I G. 7



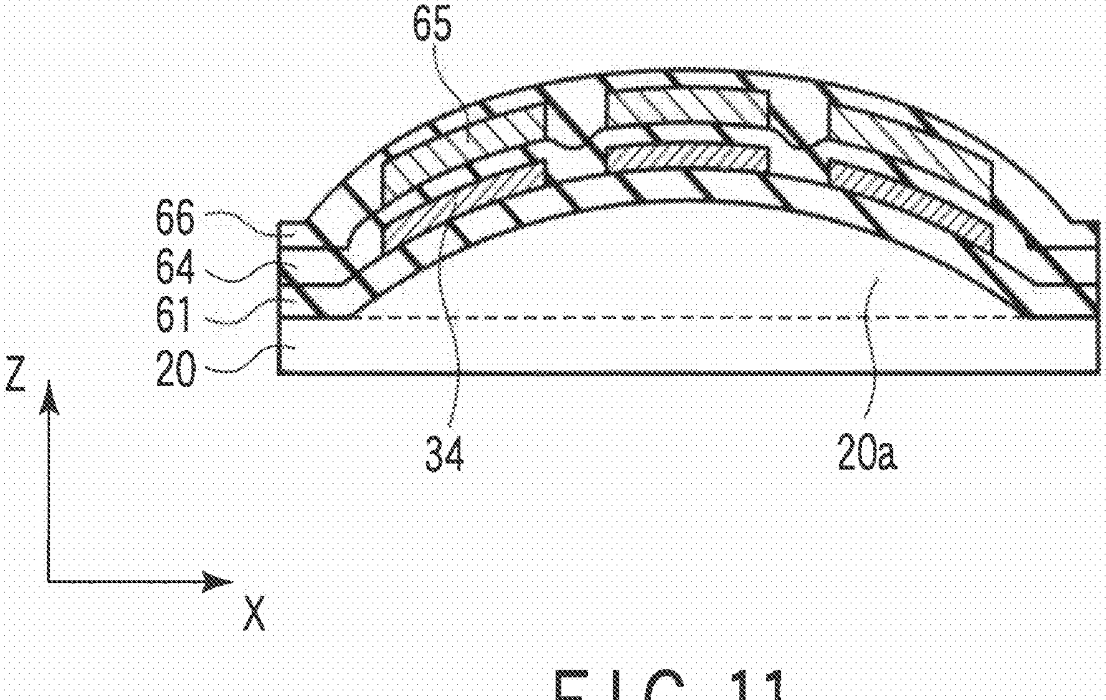
F I G. 8



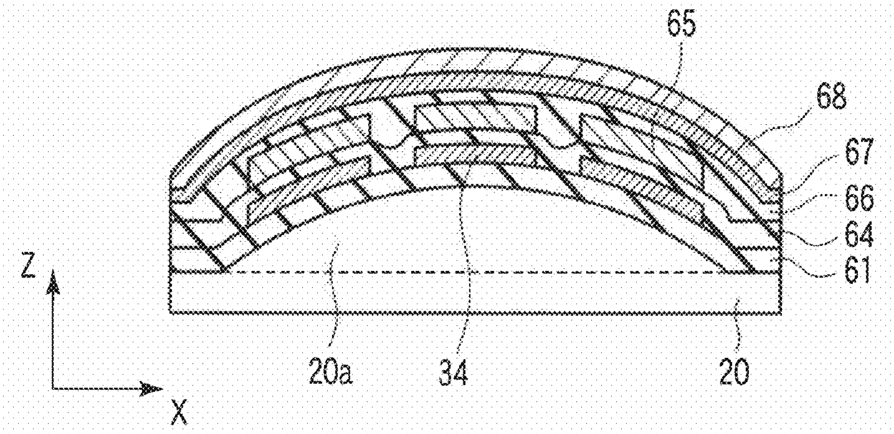
F I G. 9



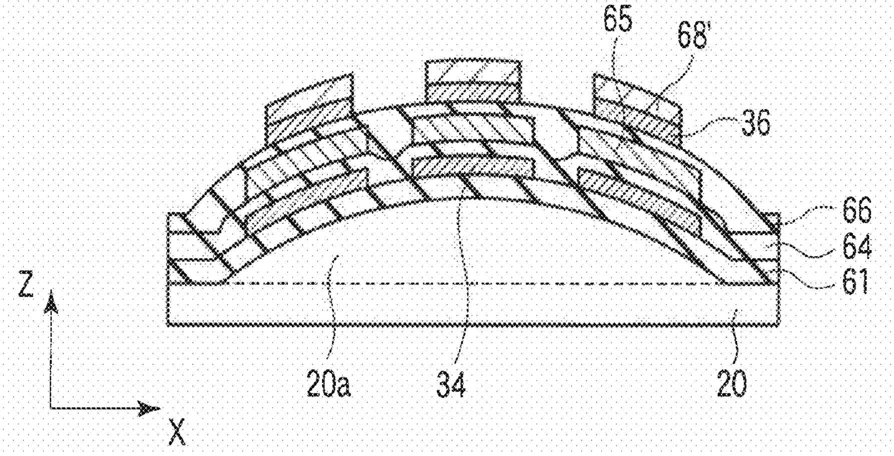
F I G. 10



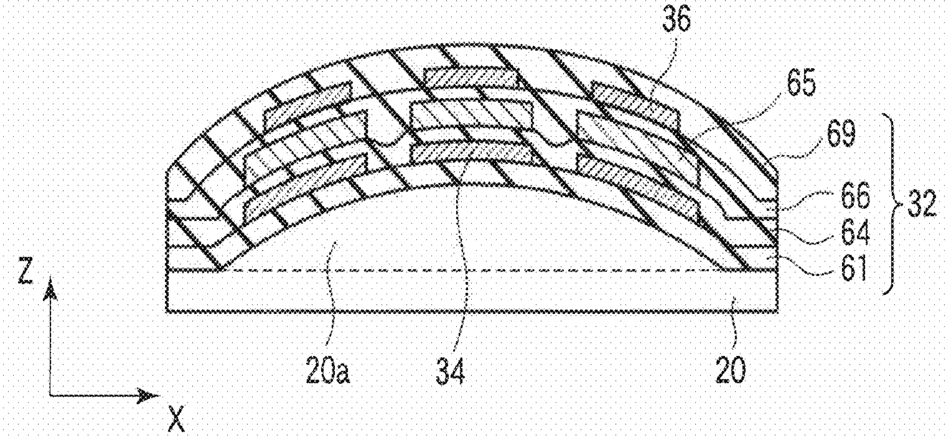
F I G. 11



F I G. 12



F I G. 13



F I G. 14

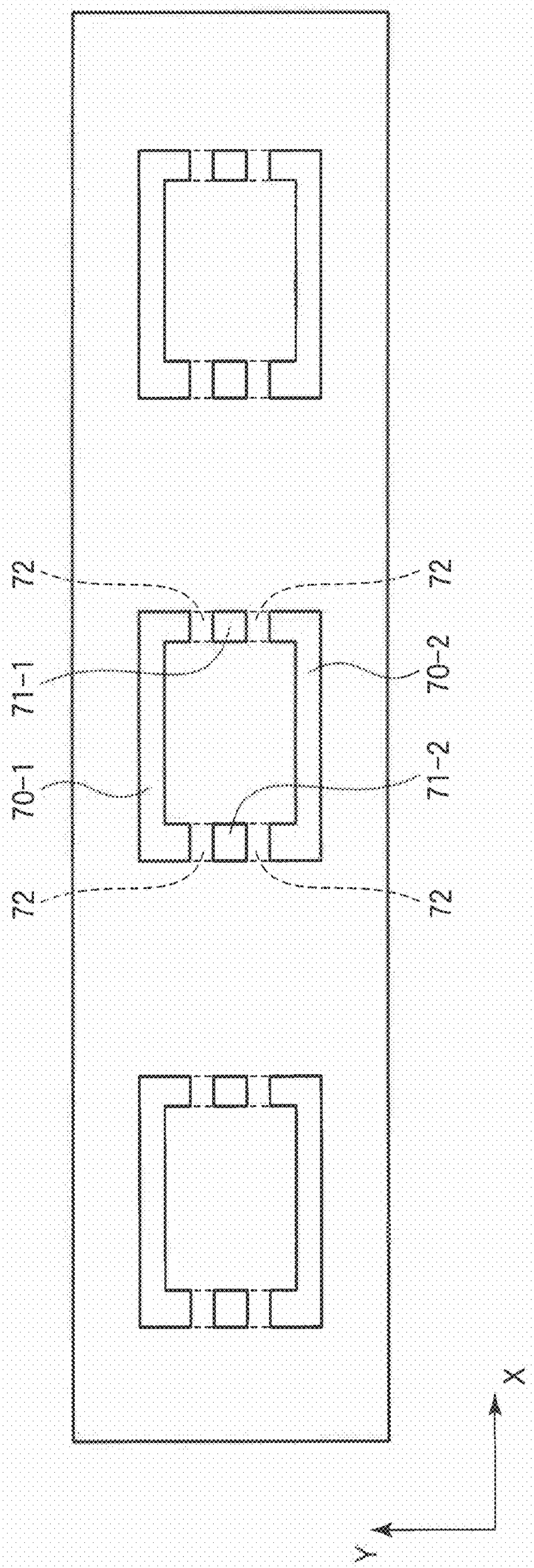
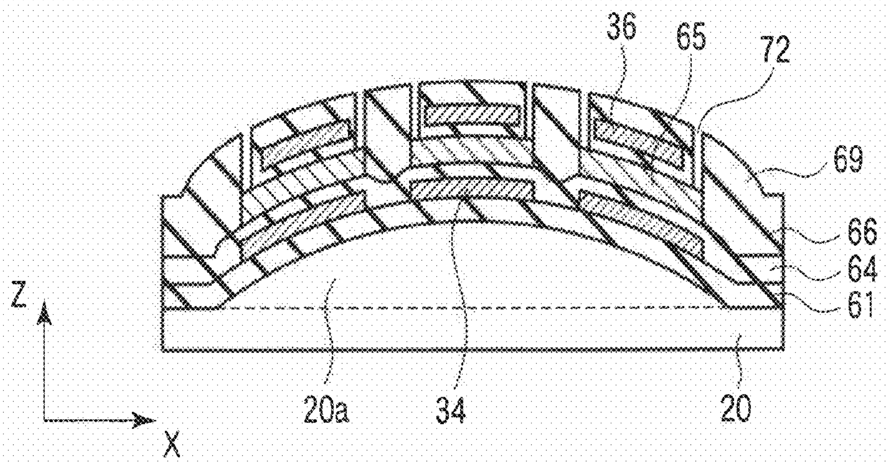
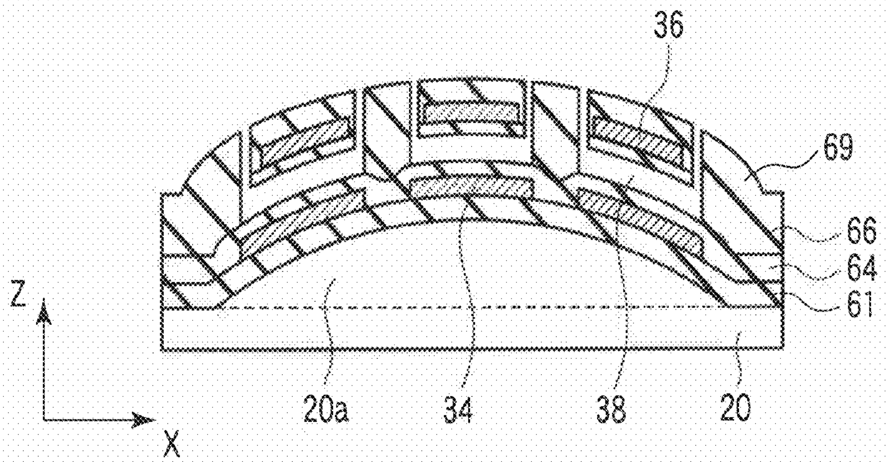


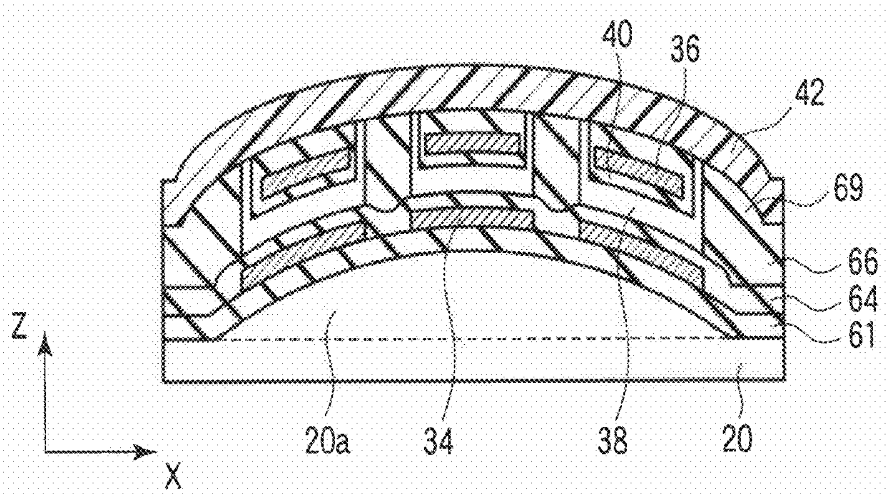
FIG. 15



F I G. 16



F I G. 17



F I G. 19

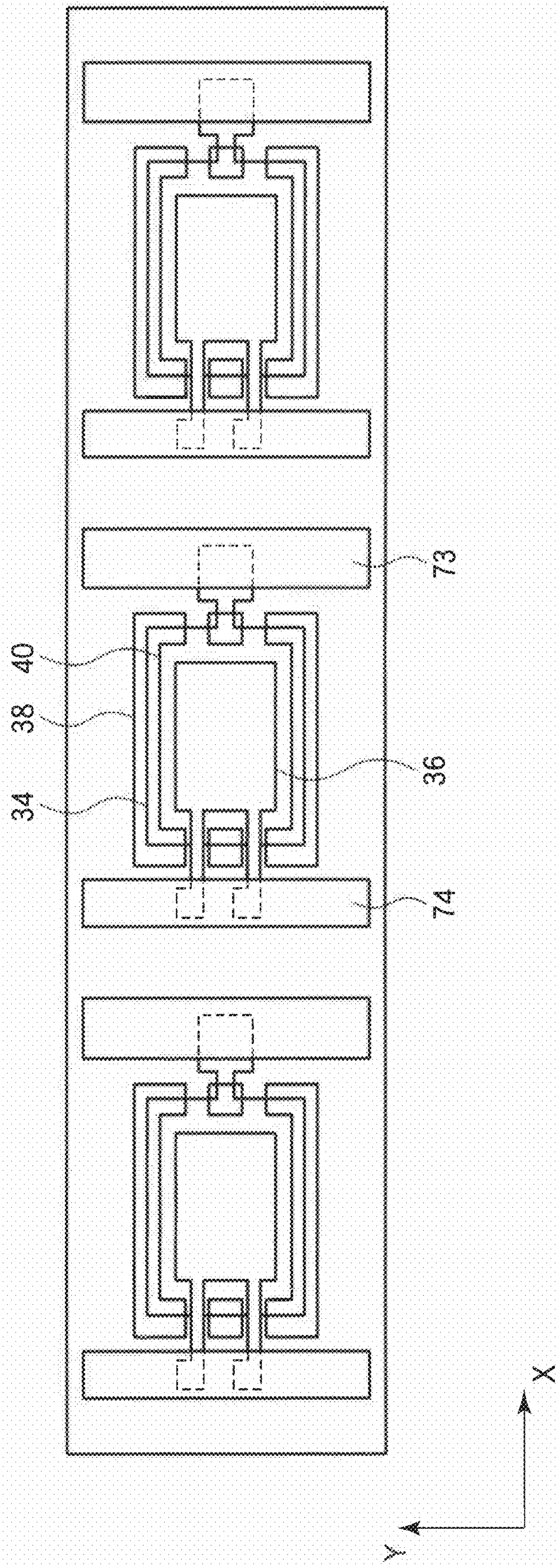


FIG. 18

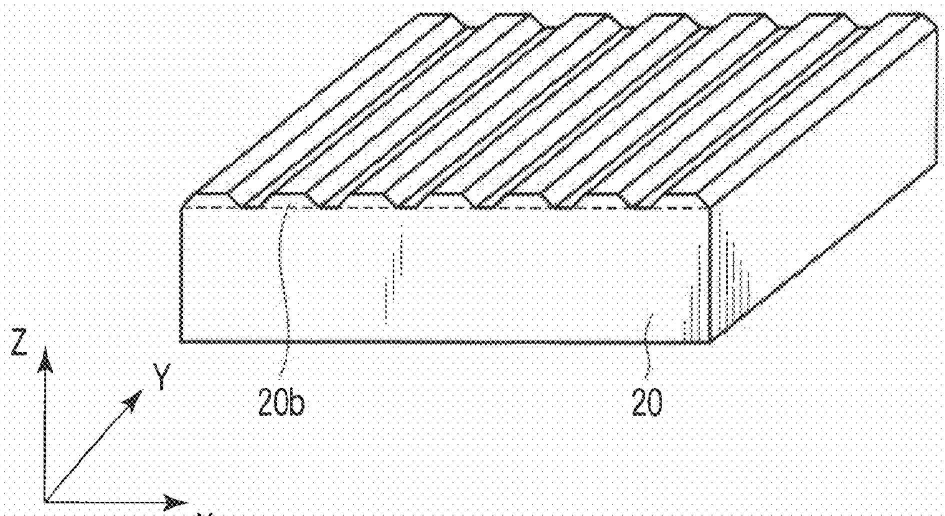

Z
Y
X
20b
20

FIG. 20

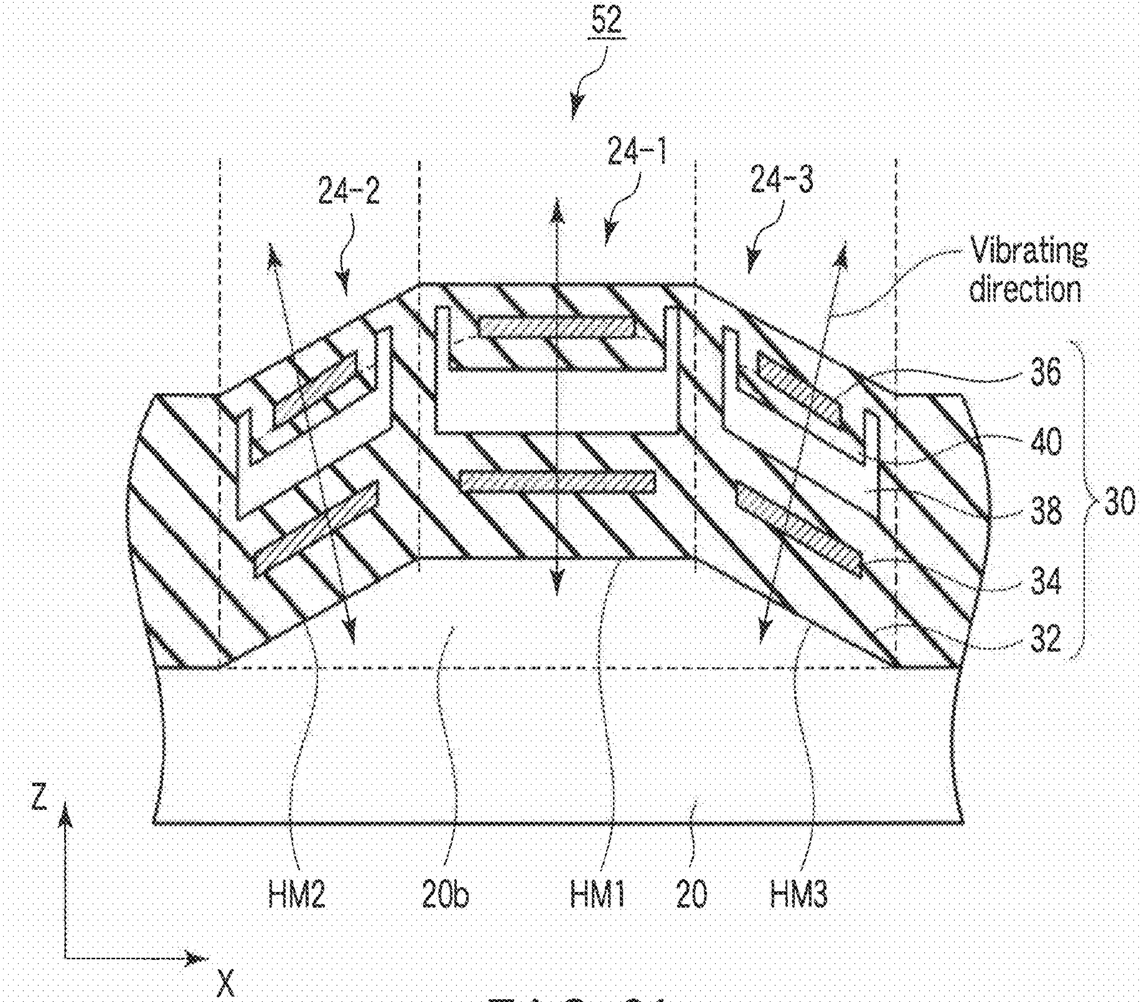
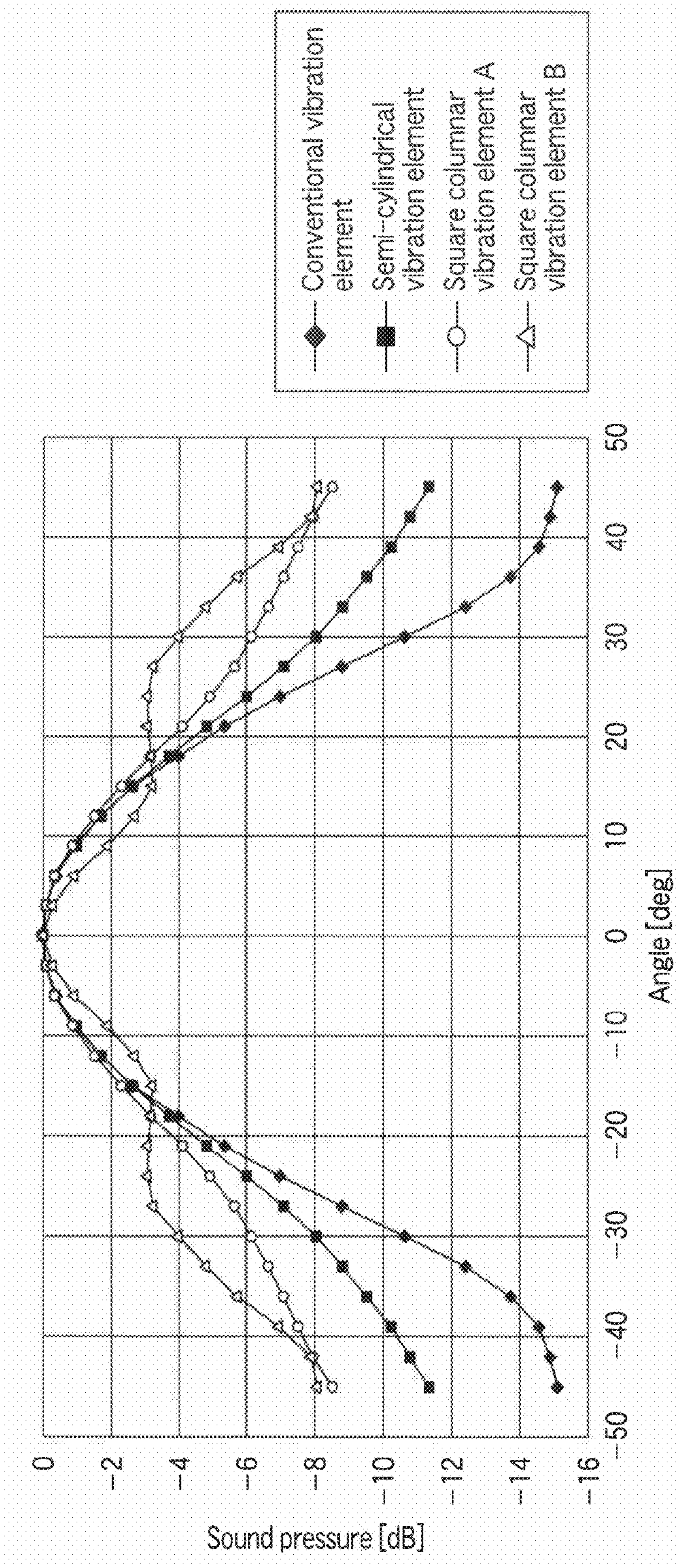
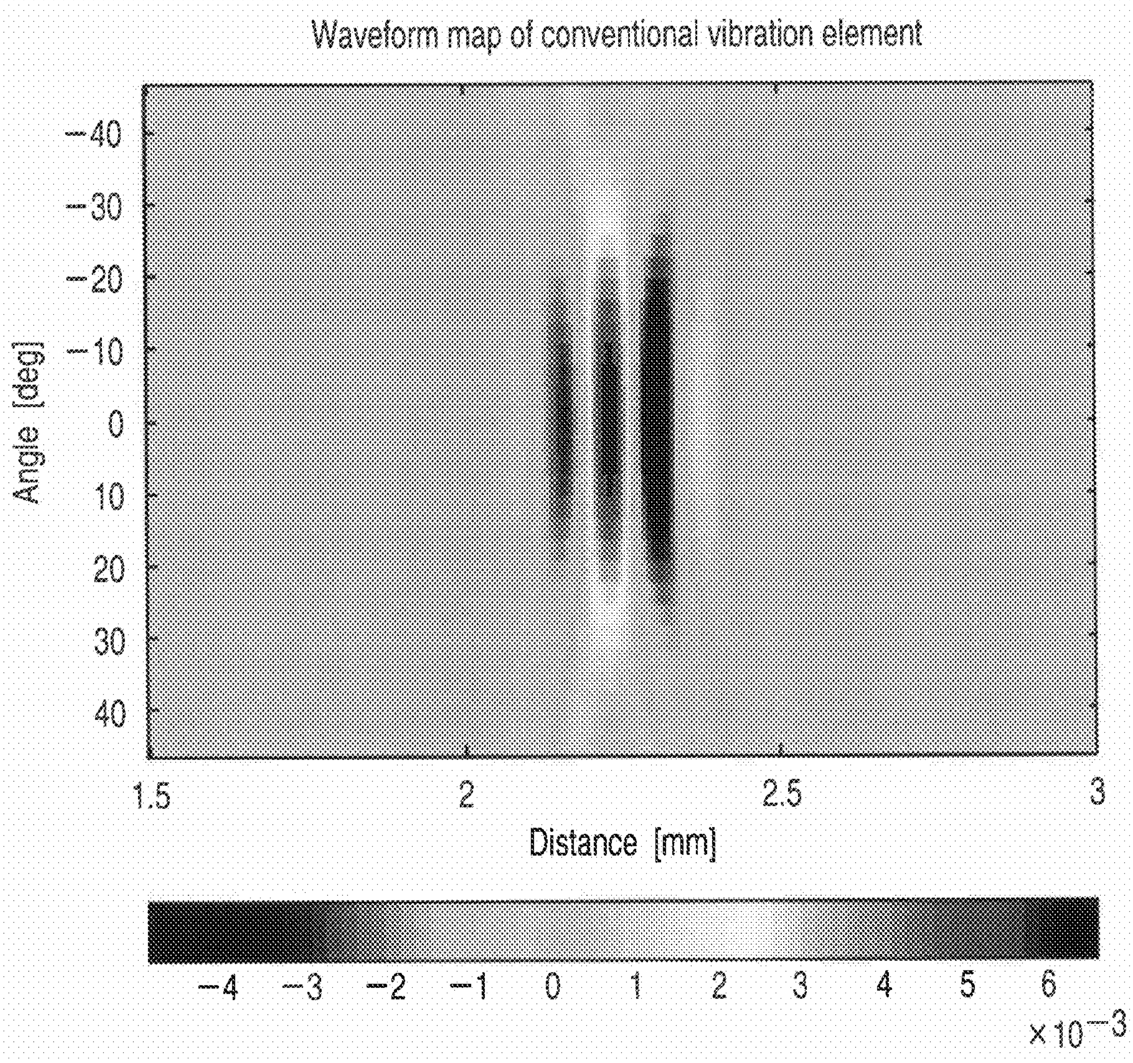

52
24-1
24-2
24-3
Vibrating direction
36
40
38
30
34
32
Z
X
HM2
20b
HM1
20
HM3

FIG. 21

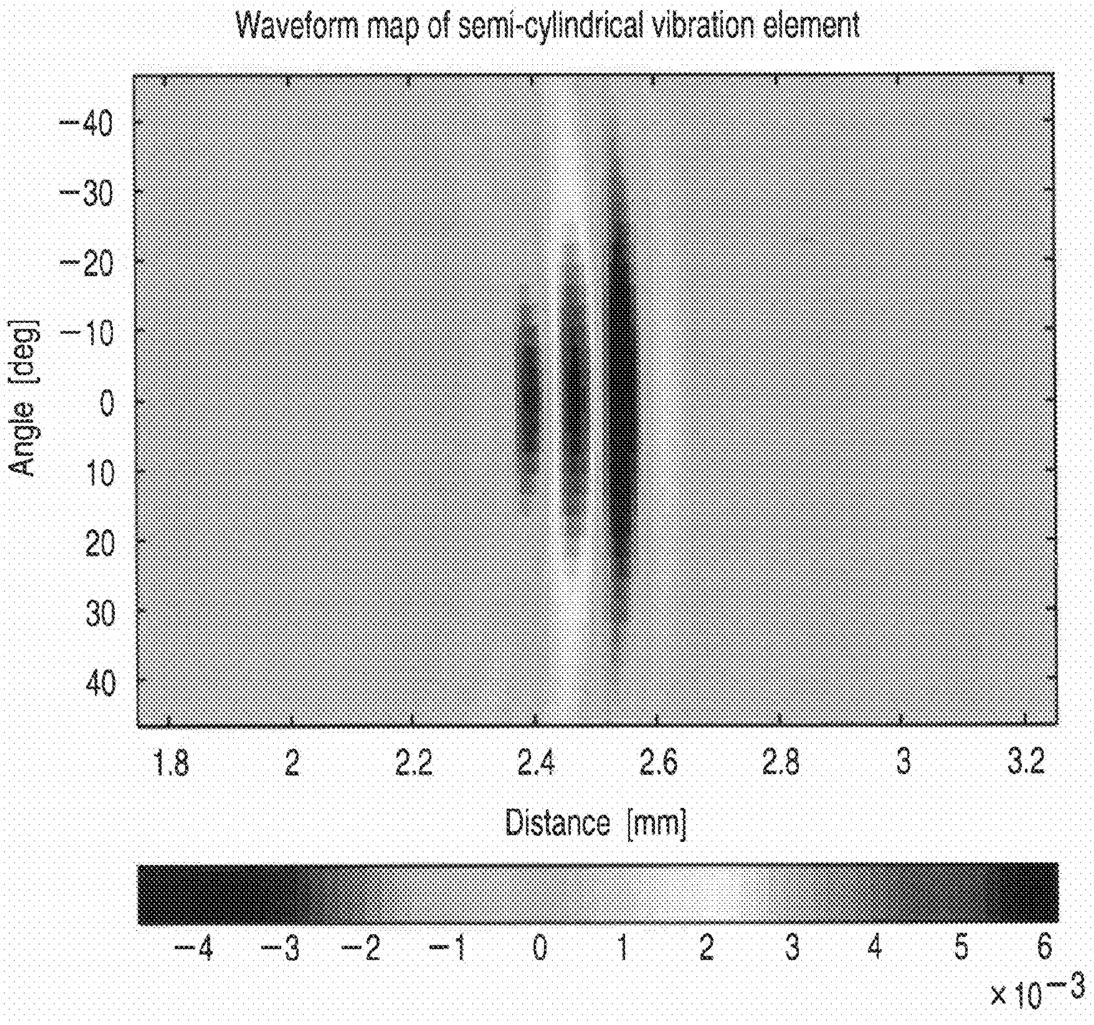

Sound pressure [dB]
0
−2
−4
−6
−8
−10
−12
−14
−16
Angle [deg]
−50
−40
−30
−20
−10
0
10
20
30
40
50
Conventional vibration element
Semi-cylindrical vibration element
Square columnar vibration element A
Square columnar vibration element B

F I G. 22

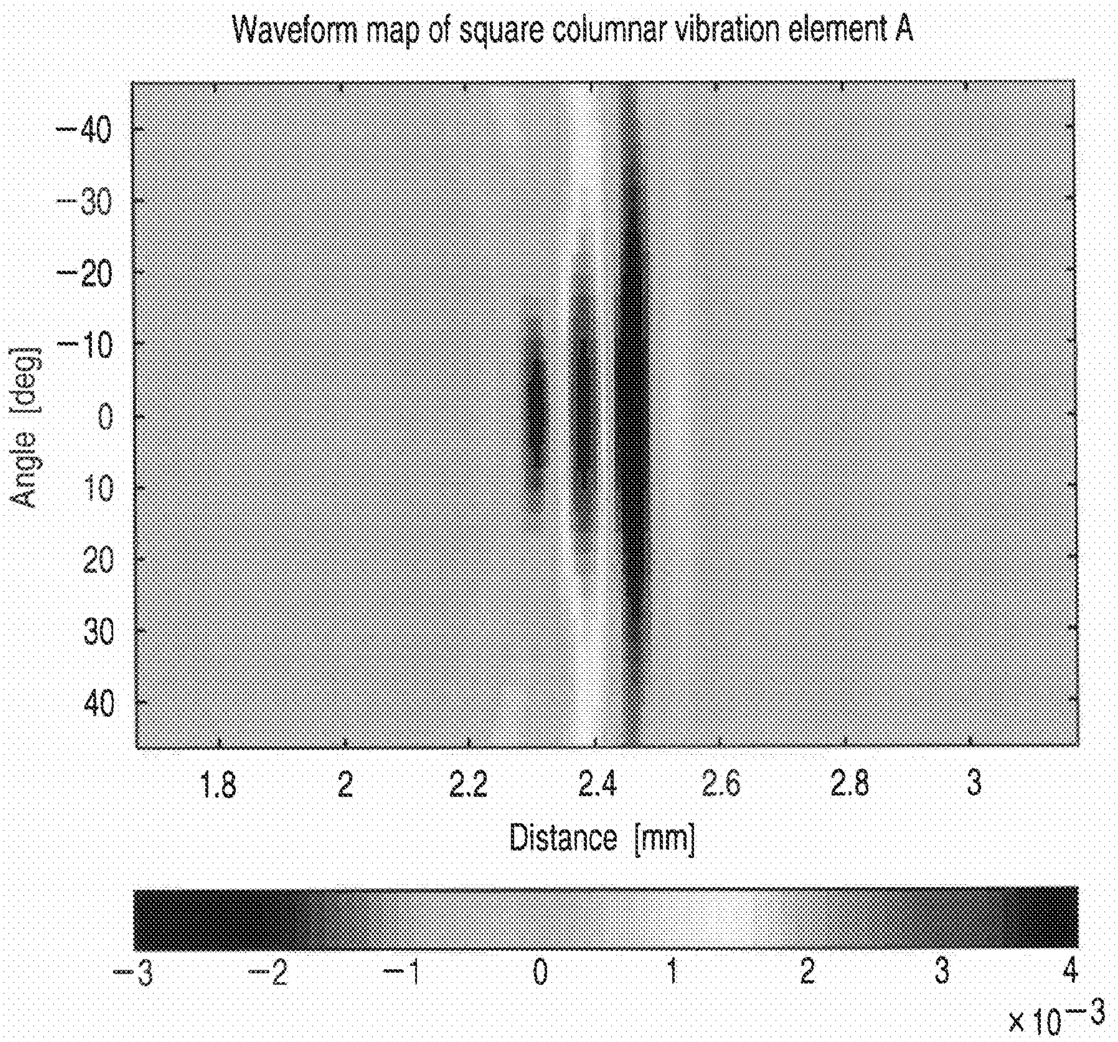


Waveform map of conventional vibration element
Angle [deg]
−40
−30
−20
−10
0
10
20
30
40
1.5
2
2.5
3
Distance [mm]
−4
−3
−2
−1
0
1
2
3
4
5
6
×10−3

F I G. 23


Waveform map of semi-cylindrical vibration element
−40
−30
−20
−10
0
10
20
30
40
Angle [deg]
1.8
2
2.2
2.4
2.6
2.8
3
3.2
Distance [mm]
−4 −3 −2 −1 0 1 2 3 4 5 6
×10−3

F I G. 24


Waveform map of square columnar vibration element A
−40
−30
−20
−10
0
10
20
30
40
Angle [deg]
1.8
2
2.2
2.4
2.6
2.8
3
Distance [mm]
−3
−2
−1
0
1
2
3
4
×10−3

F I G. 25

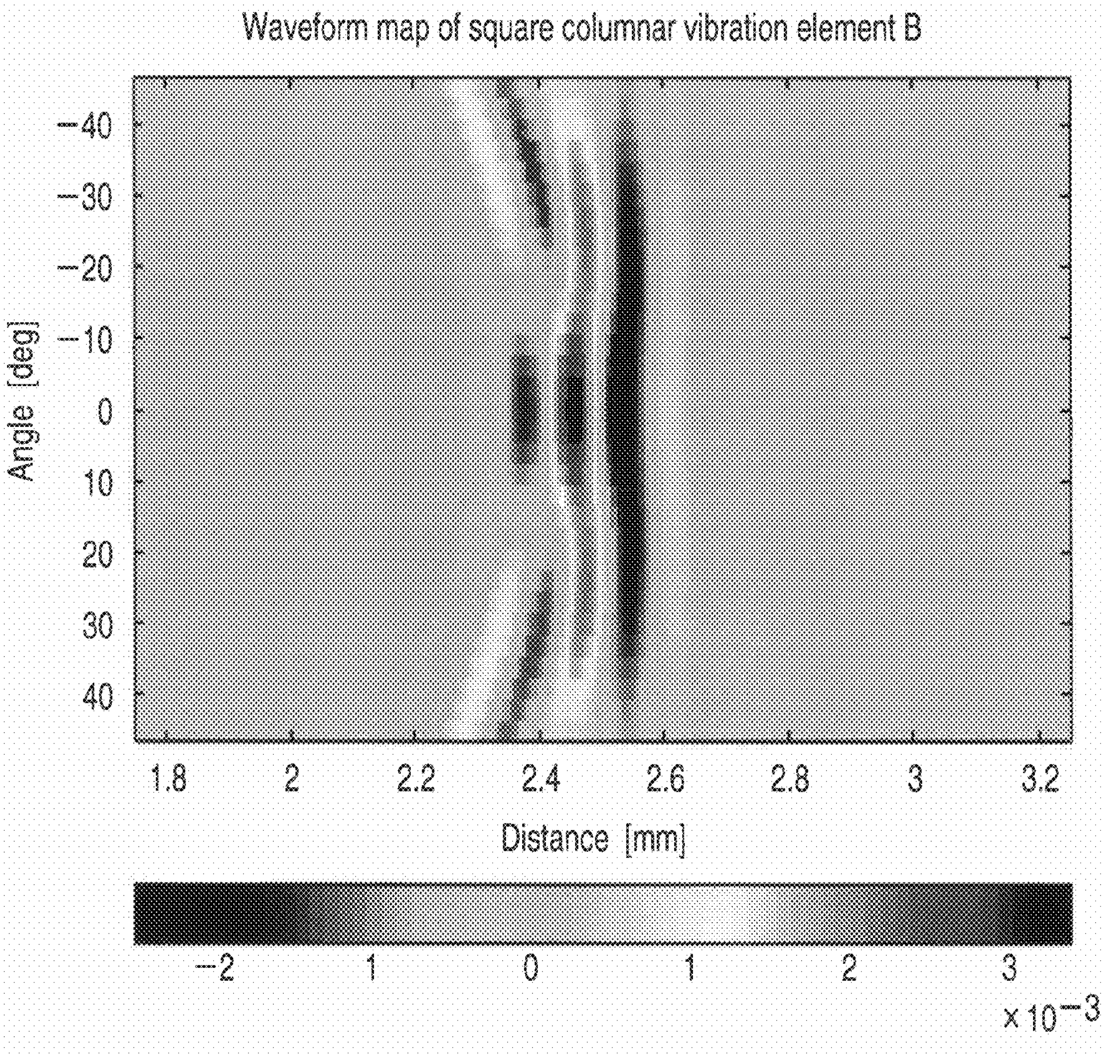
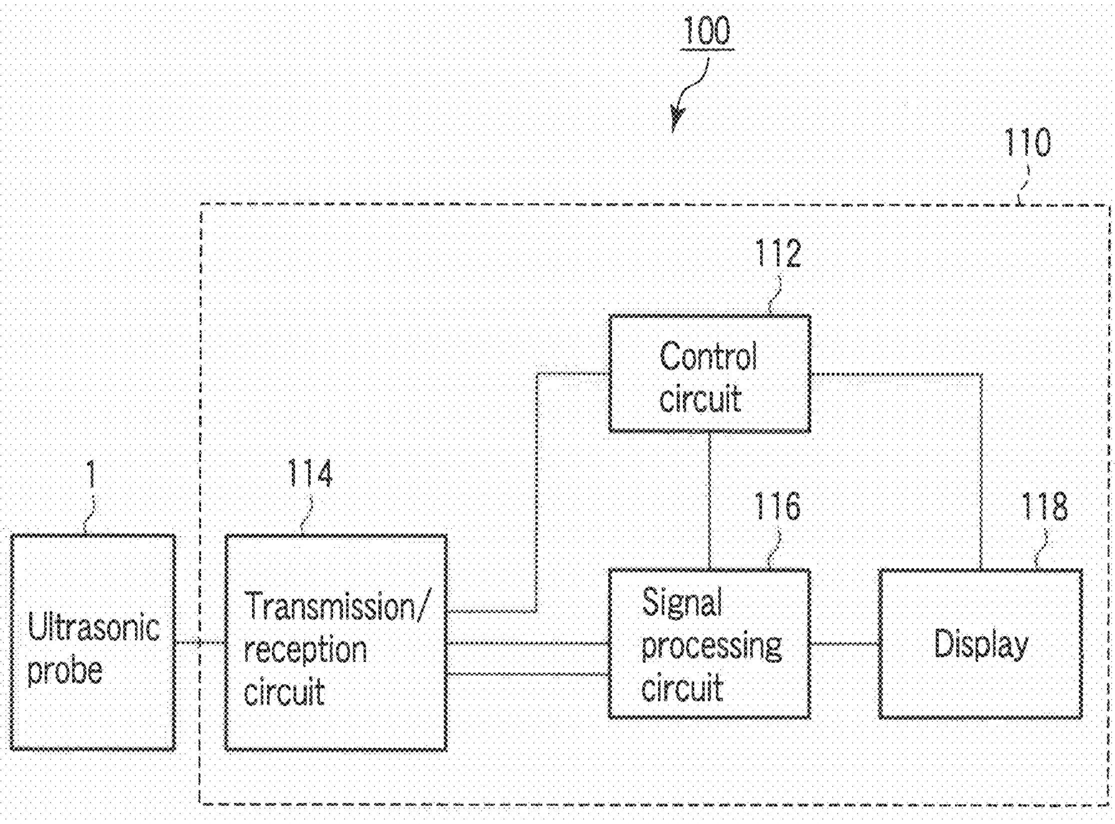
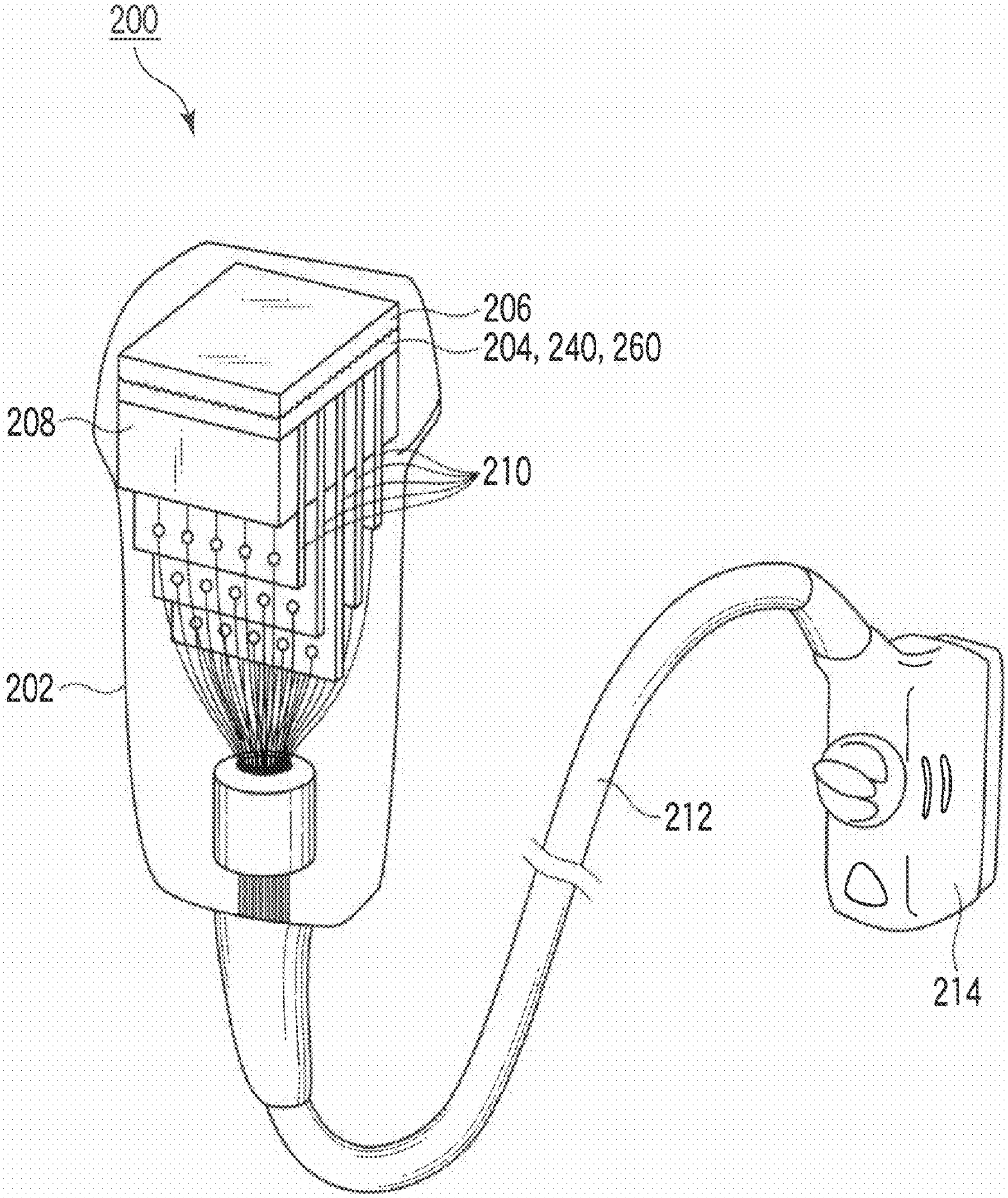

Waveform map of square columnar vibration element B
−40
−30
−20
−10
0
10
20
30
40
Angle [deg]
1.8
2
2.2
2.4
2.6
2.8
3
3.2
Distance [mm]
−2
1
0
1
2
3
x 10−3

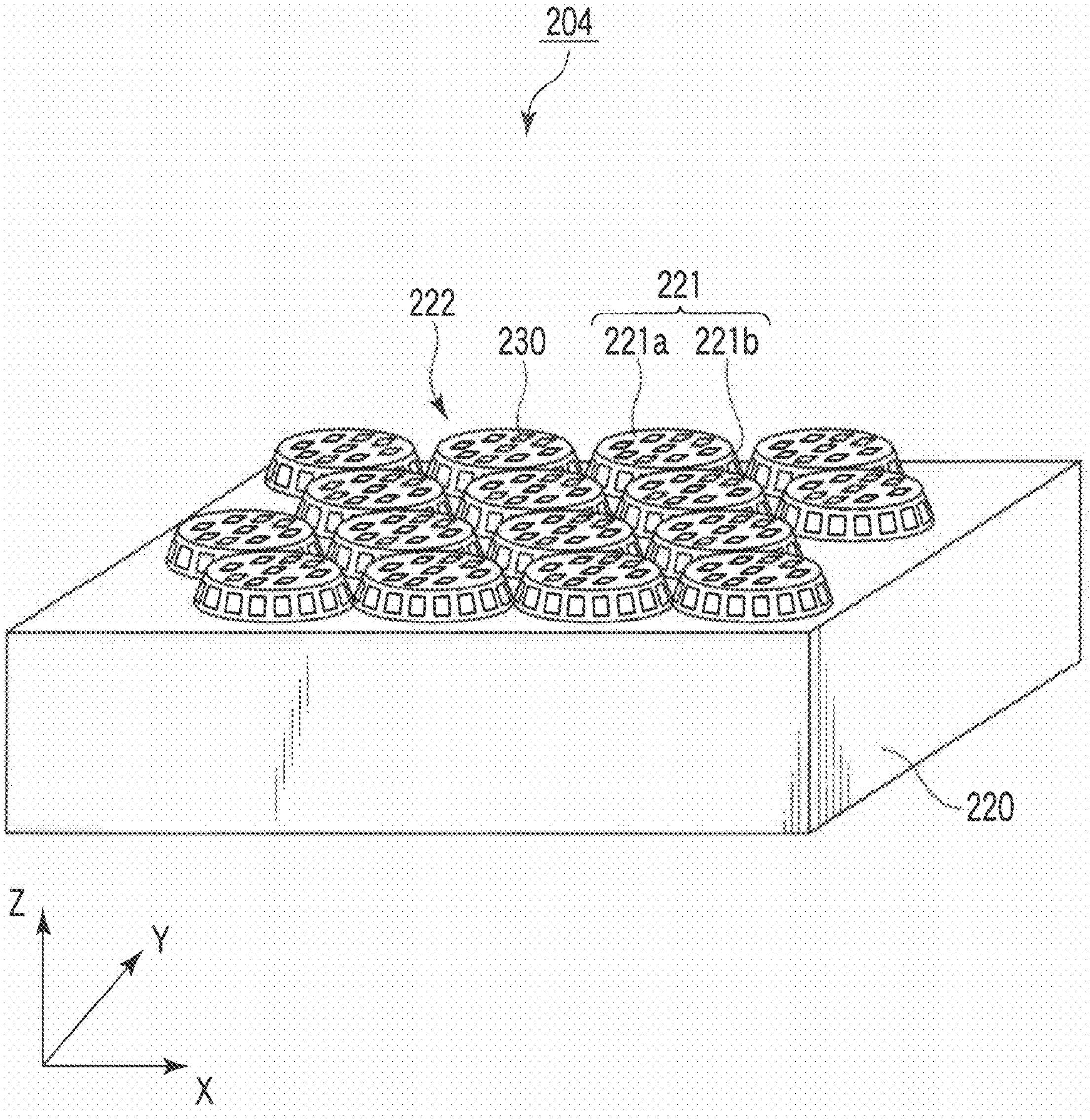
FIG. 26


100
110
112
Control circuit
1
114
116
118
Ultrasonic probe
Transmission/ reception circuit
Signal processing circuit
Display

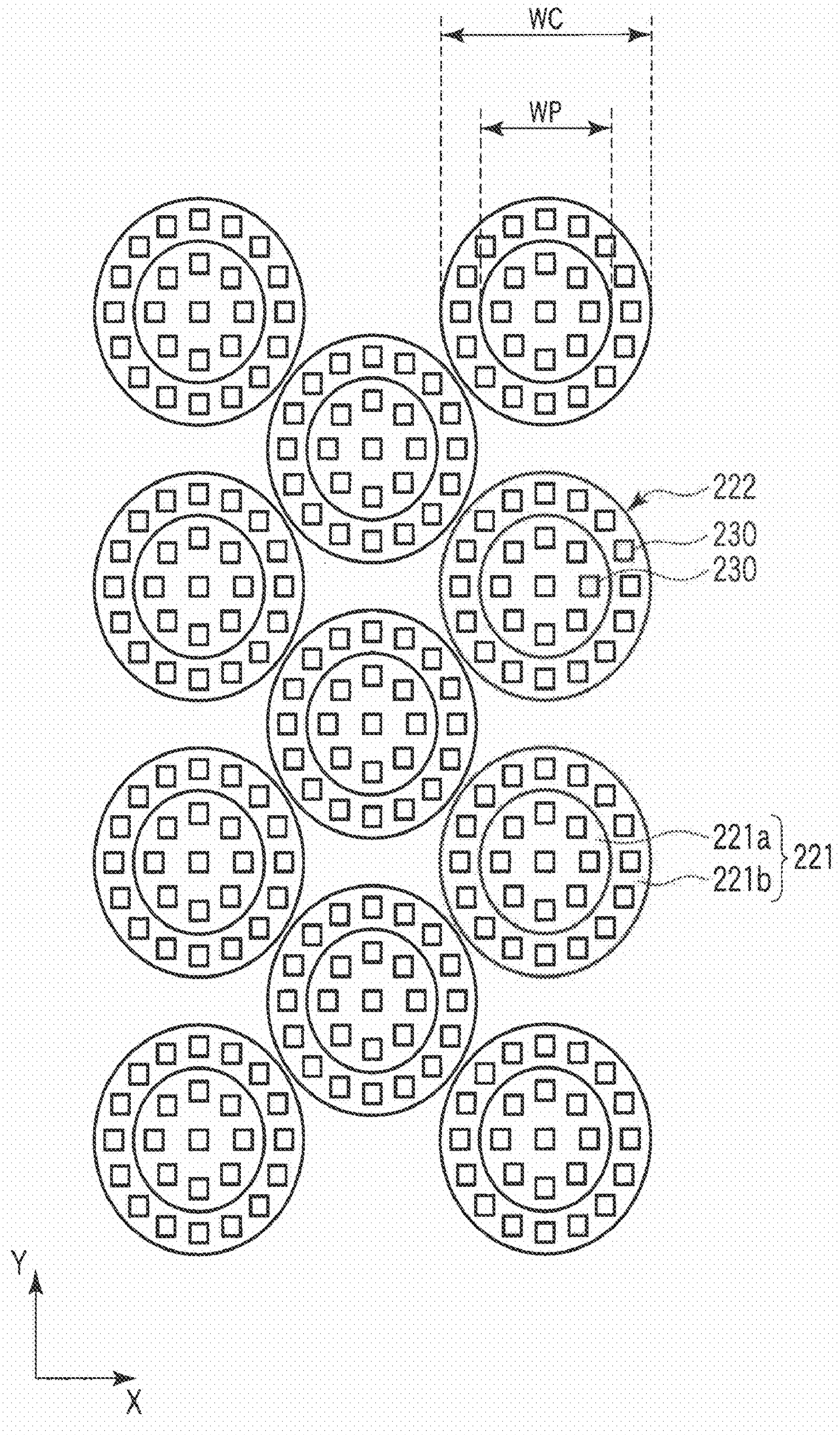
F I G. 27



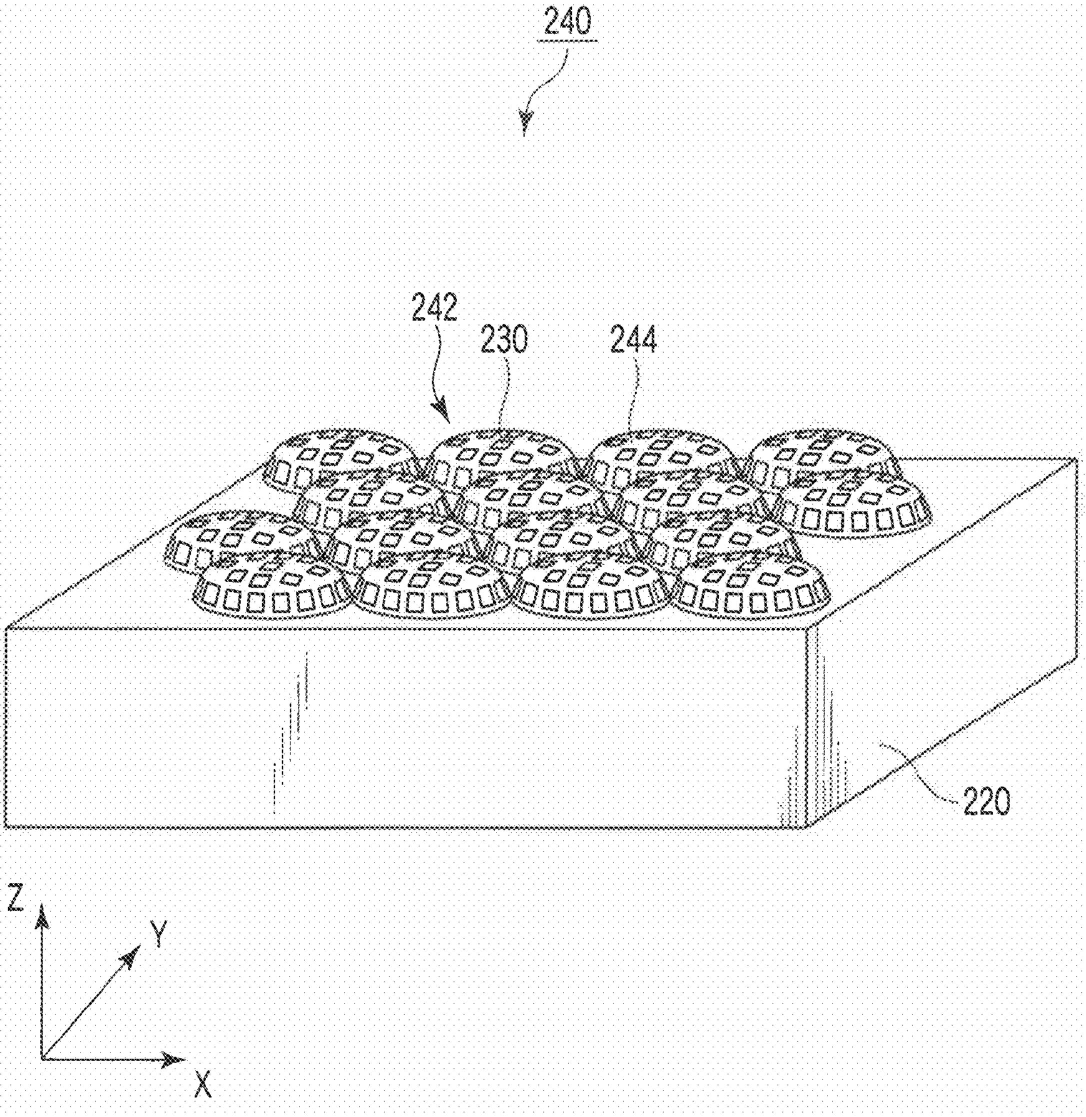
F I G. 28



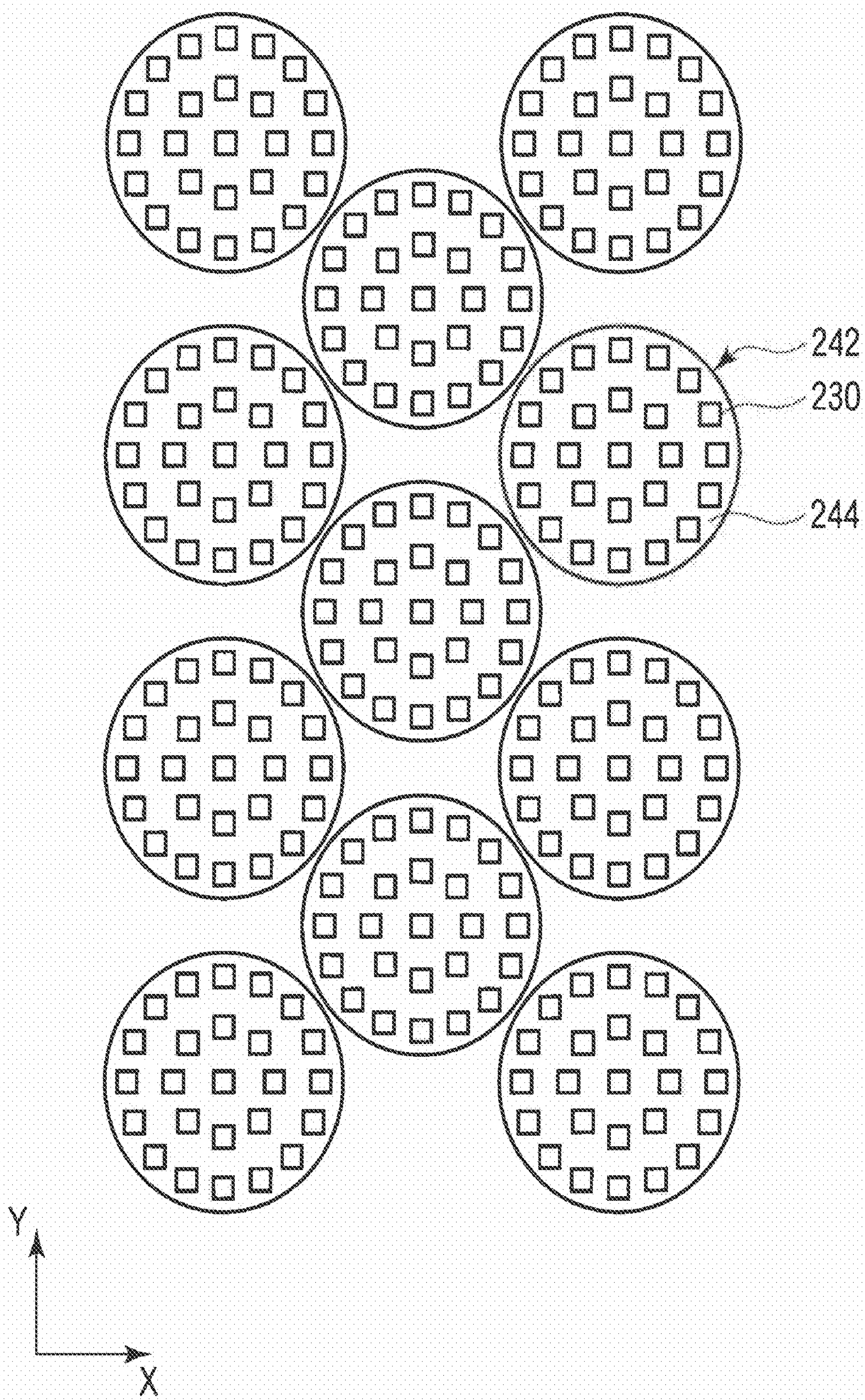
F I G. 29



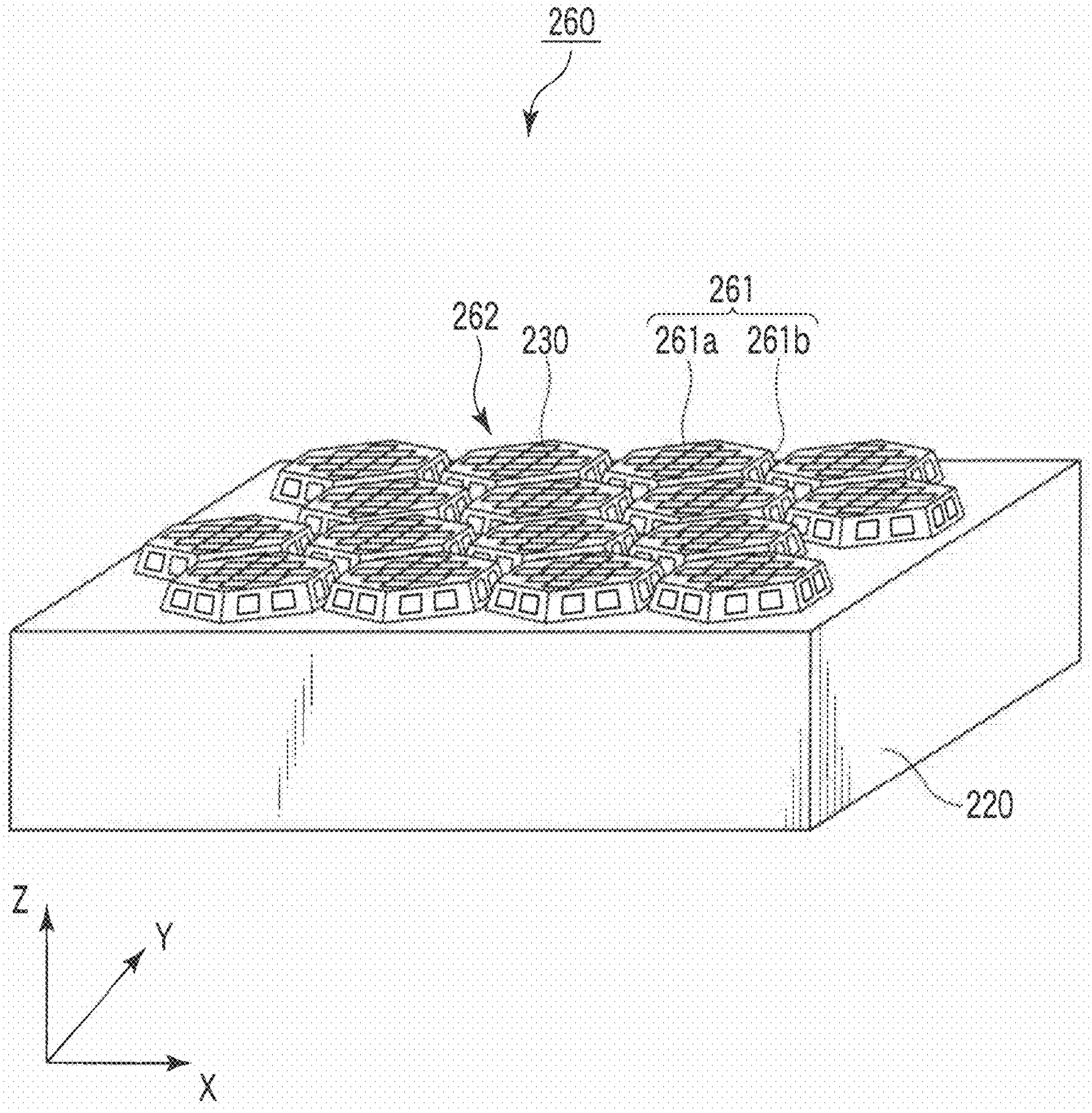
F I G. 30



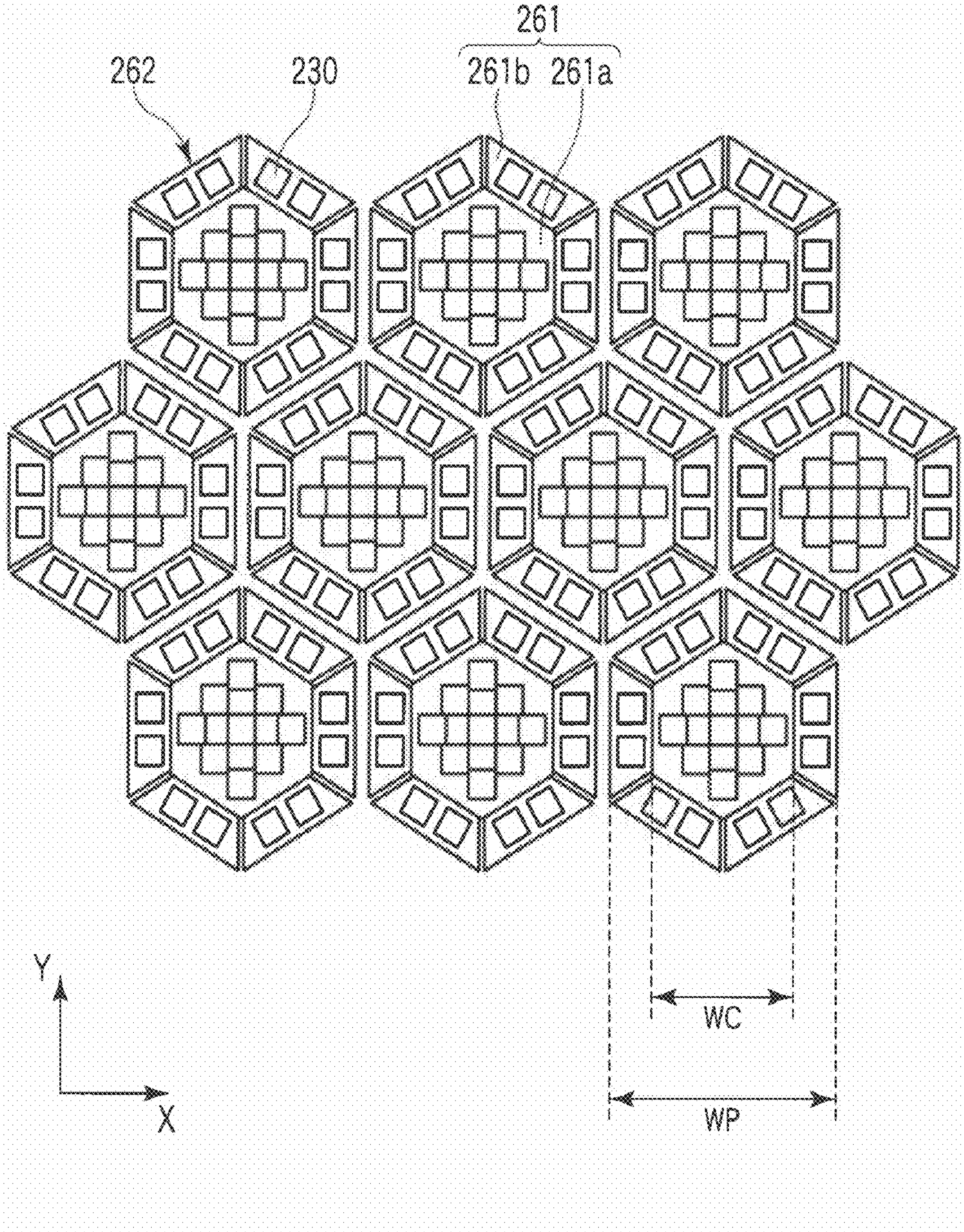
F I G. 31



F I G. 32



F I G. 33



F I G. 34

ULTRASONIC PROBE AND ULTRASONIC DIAGNOSTIC APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based upon and claims the benefit of priority from prior Japanese Patent Applications No. 2008-029688, filed Feb. 8, 2008; and No. 2009-017535, filed Jan. 29, 2009, the entire contents of both of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to an ultrasonic probe and an ultrasonic diagnostic apparatus using a micromachining ultrasound transducer (MUT).

[0004] 2. Description of the Related Art

[0005] An ultrasonic probe drives a plurality of vibration elements to radiate ultrasonic waves therefrom. The ultrasonic waves reflected by a subject or the like are received by the plurality of vibration elements.

[0006] Phase-controlled ultrasonic waves are superposed for delay control of the plurality of vibration elements to form an ultrasonic beam. At this point, the width of the vibration elements is designed to be about half of the wavelength of a center frequency to prevent a reduction in the directivity of the vibration elements.

[0007] For example, when the ultrasonic beam is inclined 30 degrees with respect to the center, its sound pressure decreases by about 3 to 6 dB as compared with sound pressure in a 0-degree direction. One reason for this is that the ultrasonic waves are not equally radiated in all directions from the vibration elements. Ultrasonic waves of higher frequencies are more sharply radiated forward and are not uniformly radiated over a wide range. Therefore, in the case of, for example, a harmonic imaging method using a high frequency band, the width of the elements has to be reduced to suit the frequency used. However, a reduced width of the elements decreases production yield or decreases power per element.

[0008] In this connection, the vibration element includes an element made mainly of piezoelectric ceramics or a capacitive micromachining ultrasound transducer (cMUT). cMUT is manufactured by processing a semiconductor substrate using a micromachining technique. The element made with piezoelectric ceramics is in the shape of a rectangular parallelepiped, while the cMUT is formed flat. Thus, the ultrasonic radiation surfaces of both types of vibration elements are flat.

[0009] Jpn. Pat. Appln. KOKAI Publication No. 2005-210710 describes a technique whereby an array of MUTs formed by flatly arranging a plurality of MUT elements is curved in order to curve the whole ultrasonic radiation surface of the MUT array. The vibration element (MUT element) described in Jpn. Pat. Appln. KOKAI Publication No. 2005-210710 is a flat vibration element.

BRIEF SUMMARY OF THE INVENTION

[0010] It is an object of the present invention to provide an ultrasonic probe and an ultrasonic diagnostic apparatus capable of maintaining directivity over a wide range.

[0011] An ultrasonic probe according to a first aspect of the present invention comprises: a base having a plurality of projections or recesses; and a plurality of MUT elements arranged in each of the projections or recesses.

[0012] An ultrasonic probe according to a second aspect of the present invention comprises: a base having a plurality of projections or recesses arrayed along at least one direction; and a plurality of vibration elements arranged in each of the projections or recesses, each of the vibration elements having ultrasonic radiation surfaces curved along the surfaces of the projections or recesses.

[0013] An ultrasonic diagnostic apparatus according to a third aspect of the present invention comprises: an ultrasonic probe according to claim **1**; a signal processing unit which subjects an echo signal from the ultrasonic probe to image processing to generate image data; and a display unit which displays the generated image data.

[0014] Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out hereinafter.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0015] The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention, and together with the general description given above and the detailed description of the embodiments given below, serve to explain the principles of the invention.

[0016] FIG. **1** is a diagram showing the entire configuration of an ultrasonic probe according to a first embodiment of the present invention;

[0017] FIG. **2** is a perspective view of a vibrator unit in FIG. **1**;

[0018] FIG. **3** is a perspective view showing a base in FIG. **2**;

[0019] FIG. **4** is a diagram showing the structure of a vibrator element in FIG. **2**;

[0020] FIG. **5** is a diagram showing the dimensional relation of the vibration element in FIG. **2**;

[0021] FIG. **6** is a diagram showing step S**2** in a process of manufacturing the vibration element in FIG. **2**;

[0022] FIG. **7** is a diagram showing step S**3** in the process of manufacturing the vibration element in FIG. **2**;

[0023] FIG. **8** is a diagram showing step S**4** in the process of manufacturing the vibration element in FIG. **2**;

[0024] FIG. **9** is a diagram showing step S**5** in the process of manufacturing the vibration element in FIG. **2**;

[0025] FIG. **10** is a diagram showing step S**6** in the process of manufacturing the vibration element in FIG. **2**;

[0026] FIG. **11** is a diagram showing step S**7** in the process of manufacturing the vibration element in FIG. **2**;

[0027] FIG. **12** is a diagram showing step S**8** in the process of manufacturing the vibration element in FIG. **2**;

[0028] FIG. **13** is a diagram showing step S**9** in the process of manufacturing the vibration element in FIG. **2**;

[0029] FIG. **14** is a diagram showing step S**10** in the process of manufacturing the vibration element in FIG. **2**;

[0030] FIG. **15** is a diagram showing step S**11** in the process of manufacturing the vibration element in FIG. **2**;

[0031] FIG. **16** is another diagram showing step S**11** in the process of manufacturing the vibration element in FIG. **2**;

[0032] FIG. **17** is a diagram showing step S**12** in the process of manufacturing the vibration element in FIG. **2**;

[0033] FIG. 18 is a plan view showing the electric system of an MUT element 30 in FIG. 2;

[0034] FIG. 19 is a diagram showing step S13 in the process of manufacturing the vibration element in FIG. 2;

[0035] FIG. 20 is a perspective view of an alternative base according to the first embodiment;

[0036] FIG. 21 is a diagram showing the structure of the vibration element equipped with the base in FIG. 20;

[0037] FIG. 22 is a graph showing a simulation result of the directivities of a conventional vibration element, a semi-cylindrical vibration element, a square columnar vibration element A and a square columnar vibration element B;

[0038] FIG. 23 is a view showing a waveform map of the conventional vibration element;

[0039] FIG. 24 is a view showing a waveform map of the semi-cylindrical vibration element according to the first embodiment;

[0040] FIG. 25 is a view showing a waveform map of the square columnar vibration element A according to the first embodiment;

[0041] FIG. 26 is a view showing a waveform map of the square columnar vibration element B according to the first embodiment;

[0042] FIG. 27 is a diagram showing the configuration of an ultrasonic diagnostic apparatus according to the first embodiment;

[0043] FIG. 28 is a diagram showing the entire configuration of an ultrasonic probe according to a second embodiment of the present invention;

[0044] FIG. 29 is a perspective view of a vibrator unit in FIG. 28;

[0045] FIG. 30 is a plan view of the vibrator unit in FIG. 29 from above;

[0046] FIG. 31 is a perspective view of an alternative to the vibrator unit in FIG. 28;

[0047] FIG. 32 is a plan view of the vibrator unit in FIG. 31 from above;

[0048] FIG. 33 is a perspective view of another alternative to the vibrator unit in FIG. 28; and

[0049] FIG. 34 is a plan view of the vibrator unit in FIG. 33 from above.

DETAILED DESCRIPTION OF THE INVENTION

[0050] Hereinafter, an ultrasonic probe and an ultrasonic diagnostic apparatus according to embodiments of the present invention will be described with reference to the drawings.

First Embodiment

[0051] FIG. 1 is a diagram showing the entire configuration of an ultrasonic probe 1 according to a first embodiment of the present invention. As shown in FIG. 1, the ultrasonic probe 1 comprises a probe case 2. A vibration element unit 4 for transmitting and receiving ultrasonic waves is contained within the probe case 2.

[0052] FIG. 2 is a perspective view of the vibration element unit 4. As shown in FIG. 2, the vibration element unit 4 has a base 20 formed of a material usable in a semiconductor process, such as a quartz (SiO_2) substrate or a silicon (Si) substrate. FIG. 3 is a perspective view showing one example of the base 20. As shown in FIGS. 2 and 3, a plurality of projections (protruded portions) 20*a* elevated in the shape of ridges are arrayed along one direction on the surface of the base 20. That is, the base 20 has a plurality of projecting surfaces. Each of the ridges runs along the one direction. The projection 20*a* has, for example, a semi-cylindrical shape. The array direction of the projections 20*a* is perpendicular to the direction of the central axes of the projections 20*a*. Here, the array direction of the projections 20*a* is defined as an X direction, the direction of the central axes of the projections 20*a* is defined as a Y direction, and the thickness direction of the base 20 perpendicular to the X and Y directions is defined as a Z direction. The projections 20*a* are elevated in the Z direction. The projections 20*a* are arrayed in parallel to each other in the Y direction.

[0053] As shown in FIG. 2, a plurality of vibration elements 22 are arranged in the plurality of projections 20*a* of the base 20 through a semiconductor process respectively. Each of the vibration elements 22 has a plurality of micromachining ultrasound transducer (MUT) arrays 24. Each of the MUT arrays 24 has a plurality of MUT elements 30 arrayed along the Y direction. One of the plurality of the MUT arrays 24 included in one vibration element 22 is arranged at the top of the projection 20*a*. The rest of the MUT arrays 24 are arranged at regular intervals on the surface of the projection 20*a*. A signal line is connected to each of the MUT elements 30. The signal lines are bundled into one for each of the vibration elements 22. That is, one vibration element 22 constitutes one channel. More specifically, the plurality of MUT elements 30 arranged in each of the vibration elements 22 combine to constitute one channel. Each of the MUT elements 30 transmits and receives ultrasonic waves. The ultrasonic radiation surface of the vibration element 22 is not flat but is curved along the surface of the projection 20*a*. The MUT element 30 can be any one of a capacitive micromachining ultrasound transducer (cMUT) and a piezoelectric micromachining ultrasound transducer (pMUT). Hereinafter, the MUT elements 30 are cMUT elements.

[0054] As shown in FIG. 1, an acoustic lens 6 is affixed to the upper surface of the vibration element unit 4 in such a manner as to be exposed out of the probe case 2. The acoustic lens 6 has a varying thickness along the Y axis, and converges the ultrasonic waves. The acoustic lens 6 also serves to protect the vibration element unit 4.

[0055] A backing (not shown) and a support 8 are affixed to the lower surface of the vibration element unit 4. The backing absorbs and damps the ultrasonic waves radiated in the rear of the vibration element unit 4, and the support 8 supports the vibration element unit 4. Moreover, a flexible printed circuit (FPC) board 10 is attached to the side surface of the vibration element unit 4. A plurality of signal lines are printed on the flexible printed circuit board 10 to independently input and output electric signals to and from the plurality of vibration elements 22 included in the vibration element unit 4.

[0056] The probe case 2 is connected to a probe connector 14 via a probe cable 12. The probe cable 12 is a covered bundle of cables 16 of the plurality of signal lines. The probe connector 14 is connected to the main unit of the ultrasonic diagnostic apparatus.

[0057] Now, details of the vibration elements 22 are described. Hereinafter, assume that the vibration element 22 has three MUT arrays 24. FIG. 4 is an XZ sectional view through three MUT elements 30 of the three MUT arrays 24 included in one vibration element 22. As shown in FIG. 4, a first MUT array 24-1 is provided at the top of the projection 20*a*, and a second MUT array 24-2 and a third MUT array

24-3 are provided on both sides of the first MUT array. In addition, three or more MUT arrays **24** may be arranged.

[0058] Each of the MUT elements **30** comprises a protective layer **32**. The protective layer **32** is deposited with a substantially equal thickness on the surface of the projection **20***a*. The material of the protective layer **32** is, for example, silicon nitride (SiN). A bottom electrode **34** and a top electrode **36** are formed inside the protective layer **32** across a cavity **38**. The bottom electrode **34** and the top electrode **36** are formed in parallel to each other. The bottom electrode **34** is maintained at a ground potential. The top electrode **36**, when used as a signal electrode, has to be shielded by a frame ground to protect a patient, but the frame ground is not described here. Although not shown, the top electrode **36** is connected to a signal line and supplied with an electric signal from the main unit of the ultrasonic diagnostic apparatus. Moreover, the protective layer **32** serves to protect the bottom electrode **34** and the top electrode **36**. A vibrating plate **40** is made of the same material as the protective layer **32**, and formed integrally with the protective layer **32**. The cavity **38** may be filled with air or some other gas, or a vacuum may be formed therein. A resin layer **42** is formed on the upper surface of the protective layer **32** over the cavity **38**.

[0059] If a time-varying voltage is applied across the bottom electrode **34** and the top electrode **36** via the unshown signal lines, attracting force or repulsive force is generated between the bottom electrode **34** and the top electrode **36** by Coulomb force depending on time. Due to the repetition of the attracting force and repulsive force, the vibrating plate **40** arranged on the lower surface of the top electrode **36** vibrates in a direction substantially perpendicular to the bottom electrode **34** and the top electrode **36** (i.e., a direction perpendicular to the surface of the projection **20***a*). Thus, ultrasonic waves are radiated in the vibrating direction by the vibration of the vibrating plate **40**. As described above, the vibration element **22** has the plurality of MUT elements **30** different from each other in vibrating direction. The plurality of MUT elements **30** arranged in the vibration element **22** simultaneously receive a drive signal from the main unit of the ultrasonic diagnostic apparatus, so that the vibration element **22** can radiate ultrasonic waves close to spherical waves. The drive signal supplied to each of the vibration elements **22** is delay-controlled to form a sharp ultrasonic beam.

[0060] Next, one example of a method of manufacturing the vibration element unit **4** is described. FIG. **5** is a diagram showing one example of the dimensional relation of the vibration element **22**. It is specifically noted here that the dimensions of each component of the vibration element unit **4** are not limited to this example. As shown in FIG. **5**, a width WV of the vibration element **22** is equal to 250 μm, an interval I between the adjacent vibration elements **22** is equal to 50 μm, a length L of the vibration element **22** is equal to 5 mm, a height H of the vibration element **22** is equal to 33.5 μm, an angle of aperture AA is equal to 30°, a width WM of the MUT element **30** is equal to 60 μm, and a base elevation angle EA at the end of the vibration element **22** is equal to 30°. In addition, the angle of aperture AA is an angle between the vibrating direction of the second MUT array **24-2** of the vibration element **22** and the vibrating direction of the third MUT array **24-3**. Moreover, the base elevation angle EA is an angle between a contact surface at the end of the projection **20***a* and a ZY plane.

[0061] The vibration element **22** is manufactured on the base **20** by use of a semiconductor process. First, the outline of an exposure system used in a lithography step in the semiconductor process is described. An optical system according to the first embodiment is roughly designed using Equation (1) and Equation (2):

$$DOF=\pm 0.5\cdot\lambda/NA^2 \tag{1}$$

$$R=k\cdot\lambda/NA \tag{2}$$

[0062] DOF: Depth of field (depth of focus)

[0063] R: Resolution

[0064] λ: Wavelength of light used for exposure

[0065] NA: Numerical aperture of lens

[0066] k: Process coefficient (a coefficient determined by process conditions and the material of a resist).

[0067] In the first embodiment, the optical system is designed with k=0.8. Moreover, DOF is set about twice as great as the height of the projection **20***a* of the base **20**, that is, set at 2'33 μm=66 μm. A krypton fluoride (KrF) excimer laser is used as a light source of the exposure system, and its wavelength is λ=0.284 μm. From these set values and from Equations (1) and (2), resolution R=4.6 μm and numerical aperture NA=0.04 are calculated. Further, the width (pattern rule) of the signal line is set at 10 μm.

[0068] In addition, the numerical aperture NA in the first embodiment is smaller than when the base **20** is flat. Accordingly, exposure time in the first embodiment is set to be longer than when the base **20** is flat.

[0069] First, a plurality of semi-cylindrical projections **20***a* are formed on the quartz substrate by machining such as dicing and by etching, such that the base **20** as shown in FIG. **3** is formed (step **S1**). In addition, the projections **20***a* are not exclusively formed by the above-mentioned method. For example, a self-assembly method may be used. Moreover, the material of the base **20** may be cast into a mold to integrally form the base **20** and the projections **20***a*.

[0070] After the base **20** has been formed, a first protective layer **61** made of, for example, silicon nitride is formed on the base **20**, as shown in FIG. **6**. A first electrode layer **62** is formed by sputtering on the upper surface of the formed first protective layer **61**. A first resist layer **63** for patterning the bottom electrode is formed on the upper surface of the formed first electrode layer **62** (step **S2**). Then, as shown in FIG. **7**, the exposure system set as described above is used to form a resist pattern **63'** for the bottom electrode **34** (step **S3**). The size of the formed resist pattern **63'** is substantially equal to that of the bottom electrode **34**. Then, as shown in FIG. **8**, the first electrode layer **62** is etched using the formed resist pattern **63'** as a mask. Thus, the bottom electrode **34** is formed (step **S4**).

[0071] After the remaining resist pattern **63'** is removed by a remover, a second protective layer **64** for protecting the bottom electrode **34** is formed on the upper surfaces of the formed bottom electrode **34** and the first protective layer **61** as shown in FIG. **9** (step **S5**). The second protective layer **64** is made of, for example, silicon nitride. After the second protective layer **64** has been formed, a sacrifice layer **65** for a resist to form the cavity **38** is formed on the upper surface of the second protective layer **64** as shown in FIG. **10** (step **S6**). Then, as shown in FIG. **11**, a third protective layer **66** functioning as a protective layer for the top electrode **36** and as the vibrating plate **40** is formed on the upper surface of the sacrifice layer **65** (step **S7**). The third protective layer **66** is made of, for example, silicon nitride. Then, as shown in FIG. **12**, a second electrode layer **67** is formed by sputtering on the upper surface of the third protective layer **66**. A resist layer **68** for patterning the top electrode is formed on the upper surface of the formed second electrode layer **67** (step S8). Then, as shown in FIG. **13**, the above-mentioned exposure system is used to form a resist pattern **68'** for the top electrode **36**, and the second electrode layer **67** is etched using the formed resist pattern **68'** as a mask. Thus, the top electrode **36** is formed (step S9).

[0072] After the remaining part of resist pattern **68'** is removed by a remover, a fourth protective layer **69** for protecting the top electrode **36** is formed on the upper surface of the formed top electrode **36** as shown in FIG. **14** (step S10). The fourth protective layer **69** is made of, for example, silicon nitride. The first protective layer **61**, the second protective layer **64**, the third protective layer **66** and the fourth protective layer **69** constitute the protective layer **32**.

[0073] Then, as shown in FIGS. **15** and **16**, a groove **70** and a vertical hole **71** are formed in the third protective layer **66** and the fourth protective layer **69**. The groove **70** and the vertical hole **71** are formed to reach the sacrifice layer **65** from the fourth protective layer **69**. The groove **70** and the vertical hole **71** are formed such that the outline of the MUT element **30** is formed (step S11). More specifically, a first groove **70-1**, a second groove **70-2**, a first vertical hole **71-1** and a second vertical hole **71-2** enclosing the top electrode **36** are formed so that four supports **72** for supporting the top electrode **36** and the vibrating plate **40** may remain.

[0074] Then, as shown in FIG. **17**, the formed vertical hole **71** is used to remove the sacrifice layer **65** by a remover, thereby forming the cavity **38** (step S12).

[0075] FIG. **18** is a plan view showing an electric system of the MUT element **30**. Before the formation of the resin layer **42**, a first through-via for drawing the bottom electrode **34** and a second through-via for drawing the top electrode **36** are formed in the fourth protective layer **69**. Then, a ground line **73** is connected to the first through-via on the third protective layer **66** or the fourth protective layer **69**, and a signal line **74** is connected to the second through-via. Thus, the signal line and the ground line are drawn from the electrodes **34** and **36**, respectively. The plurality of MUT elements **30** included in one MUT array **24** is connected to one signal line, and three signal lines of three MUT arrays **24** included in one vibration element **22** are connected to one signal line via the second through-via. That is, one vibration element **22** constitutes one channel.

[0076] After the signal line and the ground line have been drawn, the resin layer **42** for covering the cavity **38** (the vertical hole **71**) is formed on the top of the fourth protective layer **69** as shown in FIG. **19** (step S13).

[0077] The projection **20*a*** is semi-cylindrical in the above explanation. However, this is not limitation. For example, a projection **20*b*** may have a square columnar shape as shown in FIG. **20**. The projection **20*b*** is trapezoidal in the XZ section. A vibration element formed in this trapezoidal projection **20*b*** is called a square columnar vibration element. Further, the vibration element **22** formed in the above-mentioned semi-cylindrical projection **20*a*** is called a semi-cylindrical vibration element **22**.

[0078] FIG. **21** is a diagram showing a ZX section of a square columnar vibration element **52**. As shown in FIG. **21**, the projection **20*b*** has a first plane HM**1** perpendicular to the Z axis, and a second plane HM**2** and a third plane HM**3** which are not parallel to each other. The first MUT array **24-1** is arranged on the first plane HM**1**, the second MUT array **24-2** is arranged on the second plane HM**2**, and the third MUT array **24-3** is arranged on the third plane HM**3**. Each of the square MUT elements **30** is mounted so that its vibrating direction is perpendicular to the plane HM to be arranged. The planes HM**1**, HM**2** and HM**3** may be completely flat or may be slightly distorted. The structure of each of the MUT elements **30** included in the MUT arrays **24** is similar to the structure of the MUT element **30** of the semi-cylindrical vibration element **22**.

[0079] Next, the ultrasonic characteristics of the semi-cylindrical vibration element **22** and the square columnar vibration element **52** are described in comparison with the ultrasonic characteristics of a conventional vibration element. FIG. **22** is a graph showing a simulation result of the directivities of the conventional vibration element, the semi-cylindrical vibration element, a square columnar vibration element A and a square columnar vibration element B.

[0080] The conventional vibration element is a piezoelectric element made of a piezoelectric ceramic. The width of the piezoelectric element used is 250 μm. The width of the piezoelectric element is designed to be half an ultrasonic wavelength. Therefore, the piezoelectric element 250 μm thick is optimum for a frequency band of transmitted ultrasonic waves of 3 MHz. On the other hand, in the case where a harmonic imaging method is used, a high band of, for example, 6 MHz is required for the transmitted ultrasonic waves. For ease of comparison of performances, a higher band of 10 MHz is taken as an example here for a simulation. For reference, an optimum width of the piezoelectric element in a conventional method is about 75 μm at a band of 10 MHz. The simulation is run here assuming 250 μm which is much greater than the element width ideal in the conventional method. That is, the width of the conventional vibration element shown in FIG. **2** is 250 μm.

[0081] With regard to the square columnar vibration element A, the vibration element width WV is equal to 250 μm, and a radius Re of an inscribed circle inscribed in the three planes HM**1**, HM**2** and HM**3** is equal to 170 μm. With regard to the square columnar vibration element B, the element width WV is equal to 366 μm, and a radius Re of an inscribed circle inscribed in the three planes is equal to 250 μm. The width of the MUT element is 60 μm in both the square columnar vibration element A and the square columnar vibration element B.

[0082] In the case of the simulation result in FIG. **22**, the transmitted ultrasonic waves of all the vibration elements are at 10 MHz. 0 deg is in a Z axis direction in the case where the center of the ultrasonic radiation surface is coincident with the origin of the XYZ coordinates. The angle [deg] indicates the angle of inclination of a point located at a distance from the center of the ultrasonic radiation surface toward the X axis from the Z axis. Sound pressure [dB] is relative sound pressure in the case where a sound pressure at 0 deg is 0 dB. Ideally, it is desirable that the sound pressure should not change with the angle. In addition, the plurality of MUT elements included in the semi-cylindrical vibration element, the square columnar vibration element A and the square columnar vibration element B simultaneously radiate ultrasonic waves. That is, the drive signal to the MUT elements is not delay-controlled.

[0083] As shown in FIG. **22**, with regard to the directivity of the conventional vibration element, the sound pressure at 45 deg has decreased to about −15 dB as compared with the sound pressure at 0 deg. The directivity of the semi-cylindrical vibration element is improved in contrast with the directivity of the conventional vibration element, so that the sound pressure at 45 deg is less decreased to about −11 dB as compared with the sound pressure at 0 deg. The directivity of the square columnar vibration element A is improved in contrast with the directivity of the conventional vibration element, so that the sound pressure at 45 deg is less decreased to about −9 dB as compared with the sound pressure at 0 deg. The directivity of the square columnar vibration element B is improved in contrast with the directivity of the semi-cylindrical vibration element, so that the sound pressure at 45 deg is less decreased to about −8 dB as compared with the sound pressure at 0 deg.

[0084] FIGS. **23**, **24**, **25** and **26** are views showing waveform maps of the conventional vibration element, the semi-cylindrical vibration element, the square columnar vibration element A and the square columnar vibration element B, respectively. In the waveform maps, the horizontal axis indicates the distance [mm] from the center of the ultrasonic radiation surface while the vertical axis indicates the angle [deg], and a sound pressure value at each point is represented by the depth of gray. It is ideal that dark gray parts be vertically straight. In other words, it is ideal that a part with higher or lower sound pressure be located at a certain distance. As shown in FIGS. **23**, **24**, **25** and **26**, the directivities of the semi-cylindrical vibration element and the square columnar vibration element A according to the first embodiment are better than the directivity of the conventional vibration element. The directivity of the square columnar vibration element B is slightly deviated from the ideal directivity due to the fact that the design parameter of this vibration element is too great. Thus, it is apparent from the sound pressure distribution and the waveform maps that the square columnar vibration element A is proper in terms of the element shape. The shape of the square columnar vibration element A is similar to the shape used for explaining FIG. **5** and FIG. **21**.

[0085] Next, the ultrasonic diagnostic apparatus equipped with the ultrasonic probe **1** is described. FIG. **27** is a diagram showing the configuration of an ultrasonic diagnostic apparatus **100**. As shown in FIG. **27**, the ultrasonic diagnostic apparatus **100** comprises the ultrasonic probe **1** and an ultrasonic diagnostic apparatus main unit **110**. The ultrasonic diagnostic apparatus main unit **110** includes a control circuit **112** as a center, a transmission/reception circuit **114**, a signal processing circuit **116** and a display **118**.

[0086] The transmission/reception circuit **114** generates a drive signal for radiating ultrasonic waves, and supplies the generated drive signal to the vibration elements **22** to cause the vibration elements **22** to radiate ultrasonic waves. The transmission/reception circuit **114** also delays and adds echo signals supplied from the vibration elements **22**. The signal processing circuit **116** subjects the echo signals supplied from the transmission/reception circuit **114** to image processing to generate image data. The generated image is, by way of example, a B mode image or a Doppler image. The display **118** displays the generated image (e.g., the B mode image or Doppler image).

[0087] In such a configuration, the vibration element unit **4** has the vibration element **22** or vibration element **52** in which the plurality of MUT elements **30** are arranged in the projections **20***a* or projections **20***b*. Thus, the ultrasonic radiation surface of the vibration element **22** or vibration element **52** is not flat but convex. As a result, the individual vibration elements **22** or vibration elements **52** can radiate ultrasonic waves close to spherical waves on a high frequency band as compared with the conventional vibration elements with the flat ultrasonic radiation surfaces. Consequently, according to the first embodiment, it is possible to provide an ultrasonic probe and an ultrasonic diagnostic apparatus capable of maintaining directivity over a wide range without forcing a small width of the vibration elements.

[0088] In addition, the base **20** has the plurality of projections **20***a*, **20***b* in the first embodiment. However, the first embodiment is not exclusively limited to this, and the base **20** may have a plurality of recesses (depressed portions). In this case, the plurality of vibration elements are arranged in the plurality of respective recesses respectively. Moreover, the plurality of MUT elements **30** are arranged in each of the recesses.

Second Embodiment

[0089] FIG. **28** is a diagram showing the entire configuration of an ultrasonic probe **200** according to a second embodiment of the present invention. As shown in FIG. **28**, the ultrasonic probe **200** comprises a probe case **202**. A vibration element unit **204** for transmitting and receiving ultrasonic waves is contained within the probe case **202**. An acoustic lens **206** is affixed to the upper surface of the vibration element unit **204** in such a manner as to be exposed out of the probe case **202**. The acoustic lens **206** is, for example, formed into a substantially square shape. A support **208** is attached to the lower surface of the vibration element unit **204**. Moreover, a plurality of flexible printed boards **210** are attached to the lower surface of the vibration element unit **204** through the support **208**. A plurality of signal lines **216** for independently inputting and outputting electric signals to and from the vibration elements **222** are printed on the flexible printed boards **210**. The probe case **202** is connected to a probe connector **214** via a probe cable **212**. The probe connector **214** is connected to the main unit of the ultrasonic diagnostic apparatus.

[0090] FIG. **29** is a perspective view of the vibration element unit **204**. FIG. **30** is a plan view of the vibrator unit **204** from above. As shown in FIGS. **29** and **30**, the vibrator unit **204** has a base **220** formed of a material usable in a semiconductor process, such as a quartz substrate or a silicon substrate. A plurality of projections **221** are two-dimensionally discretely arranged on the surface of the base **220**. That is, the base **220** has a plurality of projections. The projection **221** has a three-dimensional structure in which a plane **221***a* substantially parallel to an XY plane is at the vertex. The plane **221***a* may be completely flat or may be slightly distorted. A curved surface **221***b* is provided to enclose the edge of the plane **221***a*. The curved surface **221***b* is formed obliquely with respect to the plane **221***a*, and connects the plane **221***a* with the surface of the base **220**. In other words, the projection **221** has such a three-dimensional structure as a cone the end of which has been removed, as shown in FIG. **29**. That is, the projection **221** is circular on the XY plane. The projections **221** are elevated in the Z direction perpendicular to the plane of the base (XY plane).

[0091] A diameter WP of the plane **221***a* is designed at, for example, 150 μm. Further, a diameter WC of the bottom surface the projection **221** is designed at, for example, 300 μm. The interval between the centers of the adjacent projections **221** is preferably constant. However, the interval between the centers of the adjacent projections **221** does not necessarily have to be constant.

[0092] The plurality of vibration elements **222** are arranged in the plurality of projections **221** by a semiconductor process respectively. Here, the vibration element **222** arranged in the projection **221** having such a three-dimensional structure as a cone the end of which has been removed is called a semi-conical vibration element **222**. The semi-conical vibration element **222** has a plurality of MUT elements **230** arranged in the plane **221***a* and the curved surface **221***b*. The signal line **216** is connected to each of the MUT elements **230**. The signal lines **216** are bundled into one for each of the semi-conical vibration element **222** in the base **220**. That is, one semi-conical vibration element **222** constitutes one channel. More specifically, the plurality of MUT elements **230** arranged in each of the semi-conical vibration element **222** combine to constitute one channel. Each of the MUT elements **230** transmits and receives ultrasonic waves. The ultrasonic radiation surface of the semi-conical vibration element **222** is curved along the surface of the projection **221**. The structure of the MUT elements **230** is similar to the structure of the MUT elements **30** according to the first embodiment.

[0093] Each of the MUT elements **230** vibrates in a direction perpendicular to the plane or the curved surface in response to the drive signal from an ultrasonic diagnostic apparatus main unit **110** (more specifically, the transmission/reception circuit **114**). Therefore, the semi-conical vibration element **222** has the plurality of MUT elements **230** different from each other in vibrating direction in the three-dimensional direction. The plurality of MUT elements **230** arranged in the semi-conical vibration element **222** simultaneously receive a drive signal from the ultrasonic diagnostic apparatus main unit **110** (more specifically, the transmission/reception circuit **114**), so that the semi-conical vibration element **222** can radiate ultrasonic waves closer to spherical waves. The drive signal supplied to each of the semi-conical vibration element **222** is delay-controlled to form a three-dimensionally sharp ultrasonic beam.

[0094] In addition, the projection **221** is not limited to such a three-dimensional structure as a cone the end of which has been removed. For example, the projection may have such a semispherical structure as a sphere half of which has been removed. A vibration element formed in the projection having a semispherical structure is hereinafter called a semispherical vibration element.

[0095] FIG. **31** is a perspective view of a vibration element unit **240** having semispherical vibration elements **242**. FIG. **32** is a plan view of the vibrator unit **240** from above. A plurality of projections **244** are two-dimensionally discretely arranged on the surface of the base **220**. The projection **244** has such a three-dimensional structure as a sphere half of which has been removed. That is, the projection **244** has one semispherical surface (semispherical surface) elevated in a Z axis direction. The semispherical vibration element **242** has the plurality of MUT elements **230** arranged in the projection **244**. Typically, one of the plurality of MUT elements **230** is arranged at the top of the projection **244**.

[0096] The angle of aperture of the projection **244** is designed at, for example, 60 degrees. The radius of a sphere inscribed in the semispherical surface is designed at, for example, 250 μm.

[0097] In addition, the projection **244** does not have to be a complete half of a sphere, and may be in the shape of a partly removed sphere. Moreover, the projection **244** does not have to be a mathematically strict sphere, and may be in the shape of a distorted sphere.

[0098] Furthermore, the shape of the projections **221** and **244** according to the second embodiment is not limited to the circular shape with respect to the XY plane. For example, the projection may be polygonal with respect to the XY plane. While any polygonal shape equal to or more than a triangular shape can be used for the projection in the second embodiment, a hexagon or octagon is preferred in particular. A vibration element formed in a projection which is hexagonal with respect to the XY plane is hereinafter called a hexagonal vibration element.

[0099] FIG. **33** is a perspective view of a vibration element unit **260** having hexagonal vibration elements **262**. FIG. **34** is a plan view of the vibrator unit **260** from above. A plurality of projections **261** which are hexagonal with respect to the XY plane are two-dimensionally discretely arranged on the surface of the base **220**. The projection **261** has a three-dimensional structure in which a plane **261***a* substantially parallel to the XY plane is at the vertex. The plane **261***a* is hexagonal with respect to the XY plane. A side surface **261***b* is provided on each of six sides of the plane **261***a*. The six side surfaces **261***b* are flat. Each of the six side surfaces **261***b* is formed obliquely with respect to the plane **261***a*, and is connected with the surface of the base **220**. That is, the projection **261** has such a three-dimensional structure as a six-sided pyramid the end of which has been removed, as shown in FIG. **33**. The hexagonal vibration element **262** has a plurality of MUT elements **230** arranged in the plane **261***a* and the six side surfaces **261***b*.

[0100] A method of manufacturing the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** is substantially similar to the three-dimensional extension of the manufacturing method described in the first embodiment. Therefore, the method of manufacturing the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** is not described. Moreover, the characteristics of ultrasonic waves radiated from the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** are substantially similar to the three-dimensional extension of the ultrasonic characteristics described in the first embodiment. Therefore, the characteristics of ultrasonic waves radiated from the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** are not described.

[0101] In such a configuration, the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** are arranged in the plurality of two-dimensionally discretely arranged projections **221**, projections **244** and projections **261**, respectively. Thus, the ultrasonic radiation surfaces of the semi-conical vibration element **222**, the semispherical vibration element **242** and the hexagonal vibration element **262** are three-dimensionally convex. As a result, the individual semi-conical vibration elements **222**, the semispherical vibration elements **242** and the hexagonal vibration elements **262** can radiate ultrasonic waves three-dimensionally close to spherical waves on a high frequency band as compared with the conventional vibration elements with the flat ultrasonic radiation surfaces. Consequently, according to the second embodiment, it is possible to provide an ultrasonic probe and an ultrasonic diagnostic apparatus capable of maintaining directivity over a wide range without forcing a small width of the vibration elements.

[0102] In addition, the base **220** has the plurality of projections **221**, projections **244** and projections **261** in the second embodiment. However, the second embodiment is not exclusively limited to this. For example, the base **220** may have a plurality of recesses. The recesses are circular or polygonal with respect to the XY plane. A plurality of vibration elements are arranged in the plurality of respective recesses respectively. Moreover, the plurality of MUT elements **230** are arranged in each of the recesses.

[0103] Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details and representative embodiments shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.

What is claimed is:

1. An ultrasonic probe comprising:

a base having a plurality of projections or recesses; and

a plurality of MUT elements arranged in each of the projections or recesses.

2. The ultrasonic probe according to claim **1**, wherein the plurality of the projections are arrayed along a first direction, each of the projections being arranged in parallel to a second direction perpendicular to the first direction, each of the projections being elevated in a third direction perpendicular to the first and second directions, each of the projections having the shape of ridge running along the second direction.

3. The ultrasonic probe according to claim **2**, wherein a plurality of vibration elements are arranged in the plurality of projections respectively,

each of the vibration elements having:

a plurality of MUT arrays arranged in the projection along the first direction,

each of the MUT arrays having:

the plurality of MUT elements arrayed in the projection along the second direction.

4. The ultrasonic probe according to claim **3**, wherein each of the projections has three planes,

one of the three planes being perpendicular to the third direction,

three or more MUT arrays being arranged in the three planes.

5. The ultrasonic probe according to claim **3**, wherein each of the projections has one surface curved in the third direction,

three MUT arrays being arranged in the curved one surface.

6. The ultrasonic probe according to claim **1**, wherein the plurality of projections are two-dimensionally discretely arrayed on the base along a first direction and a second direction substantially perpendicular to the first direction, each of the projections being elevated in a third direction perpendicular to the first and second directions.

7. The ultrasonic probe according to claim **6**, wherein a plurality of vibration elements are arranged in the plurality of projections respectively, and

each of the vibration elements has the plurality of MUT elements arranged in the first and second directions.

8. The ultrasonic probe according to claim **7**, wherein each of the projections has six or eight planes,

one of the six or eight planes being substantially perpendicular to the third direction,

the plurality of MUT elements being arranged in the six or eight planes.

9. The ultrasonic probe according to claim **7**, wherein each of the plurality of projections has one plane and one curved surface,

the one plane being substantially perpendicular to the third direction,

the plurality of MUT elements being arranged in the one plane and the one curved surface.

10. The ultrasonic probe according to claim **7**, wherein each of the projections has one semispherical surface,

the semispherical surface being elevated in the third direction,

the plurality of MUT elements being arranged in the semispherical surface.

11. An ultrasonic probe comprising:

a base having a plurality of projections or recesses arrayed along at least one direction; and

a plurality of vibration elements arranged in the plurality of projections or recesses respectively, each of the vibration elements having ultrasonic radiation surfaces curved along the surfaces of each of the projections or recesses.

12. The ultrasonic probe according to claim **11**, wherein each of the vibration elements has a plurality of MUT elements, the plurality of MUT elements being arranged in each of the projections or recesses.

13. The ultrasonic probe according to claim **11**, wherein each of the vibration elements constitutes one channel.

14. An ultrasonic diagnostic apparatus comprising:

an ultrasonic probe according to claim **1**;

a signal processing unit which subjects an echo signal from the ultrasonic probe to image processing to generate image data; and

a display unit which displays the generated image data.

* * * * *

专利名称(译)	超声波探头和超声波诊断仪		
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摘要(译)

底座具有多个凸起或凹槽。每个凸起或凹陷对应于一个振动元件通道。每个振动元件具有多个MUT元件。每个MUT元件发送和接收超声波。多个MUT元件布置在每个凸起或凹陷中。因此，每个振动元件可以发送和接收具有沿着凸起或凹陷的表面弯曲的辐射表面的超声波。