US010177732B2

(12) **United States Patent**
Yokoyama

(10) **Patent No.: US 10,177,732 B2**
(45) **Date of Patent: Jan. 8, 2019**

(54) **PIEZOELECTRIC THIN FILM RESONATOR, FILTER, AND DUPLEXER**

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(72) Inventor: **Tsuyoshi Yokoyama**, Tokyo (JP)

(73) Assignee: **TAIYO YUDEN CO., LTD.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 172 days.

(21) Appl. No.: **15/214,786**

(22) Filed: **Jul. 20, 2016**

(65) **Prior Publication Data**

US 2017/0033769 A1 Feb. 2, 2017

(30) **Foreign Application Priority Data**

Jul. 29, 2015 (JP) 2015-150045

(51) **Int. Cl.**

H03H 9/02	(2006.01)
H03H 9/13	(2006.01)
H03H 9/17	(2006.01)

(52) **U.S. Cl.**

CPC ***H03H 9/02015*** (2013.01); ***H03H 9/13*** (2013.01); ***H03H 9/173*** (2013.01);
(Continued)

(58) **Field of Classification Search**

CPC H03H 3/02; H03H 9/706; H03H 9/02118; H03H 9/173; H03H 9/175; H03H 2003/021; H03H 9/02015; Y10T 29/42
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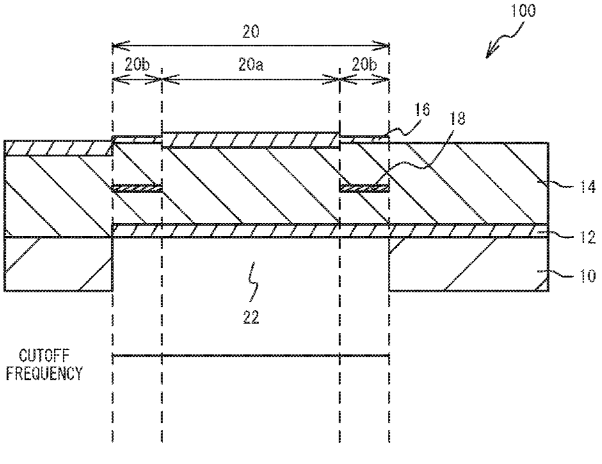
Primary Examiner — Robert J Pascal
Assistant Examiner — Jorge Salazar, Jr.
(74) *Attorney, Agent, or Firm* — Chen Yoshimura LLP

(57) **ABSTRACT**

A piezoelectric thin film resonator includes: a substrate; a piezoelectric film located on the substrate and having a Poisson's ratio of 0.33 or less; a lower electrode and an upper electrode facing each other across the piezoelectric film; and an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region, wherein at least one of the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region.

19 Claims, 25 Drawing Sheets



(52) **U.S. Cl.**
CPC ***H03H 9/174*** (2013.01); ***H03H 9/175*** (2013.01); *H03H 9/02118* (2013.01)

(58) **Field of Classification Search**
USPC 333/133, 187, 188
See application file for complete search history.

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U.S. Appl. No. 15/417,725, filed Jan. 27, 2017.

Japanese Office Action dated Apr. 3, 2018, in a counterpart Japanese patent application No. 2016-020952. A machine translation (not reviewed for accuracy) attached.).

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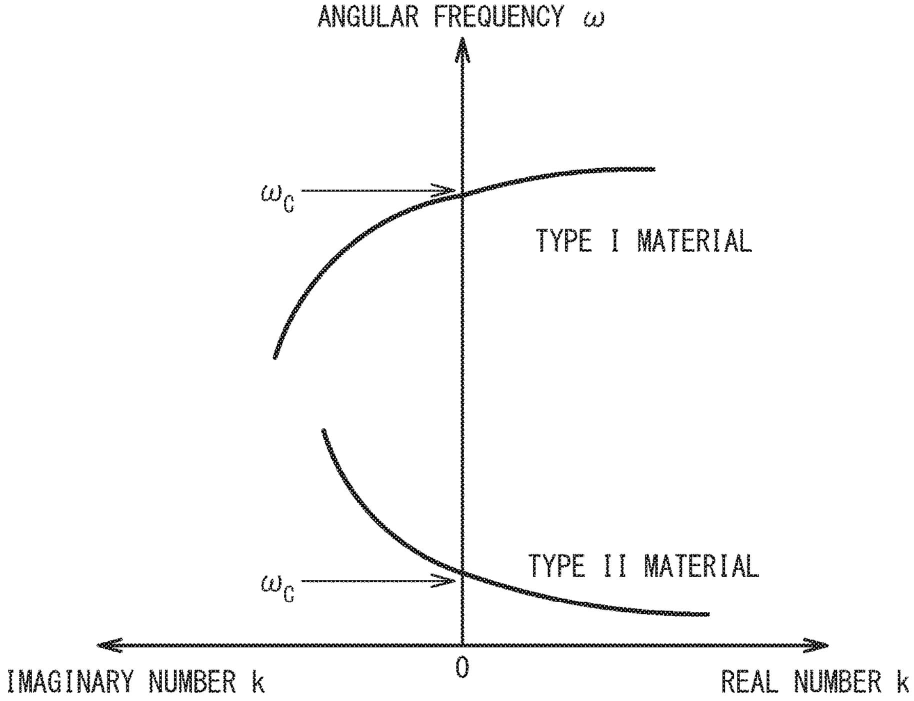
FIG. 1


ANGULAR FREQUENCY ω
ω_C
TYPE I MATERIAL
TYPE II MATERIAL
ω_C
IMAGINARY NUMBER k
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REAL NUMBER k

FIG. 2

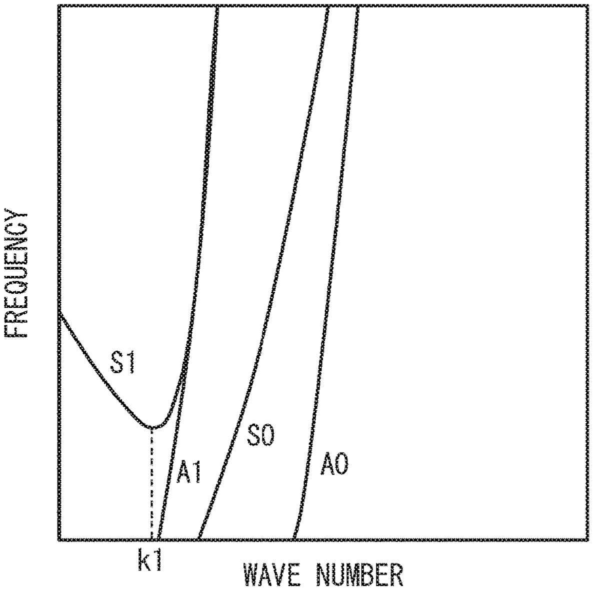


FIG. 3A

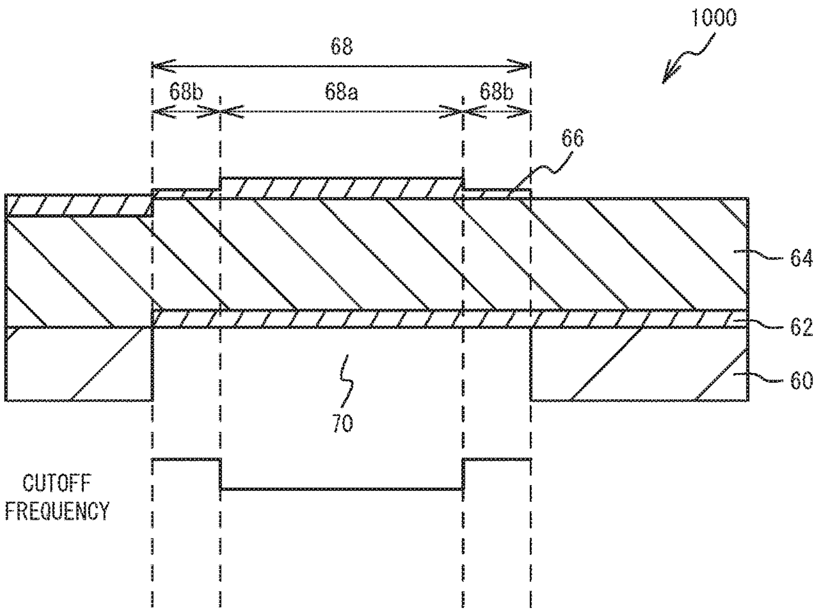
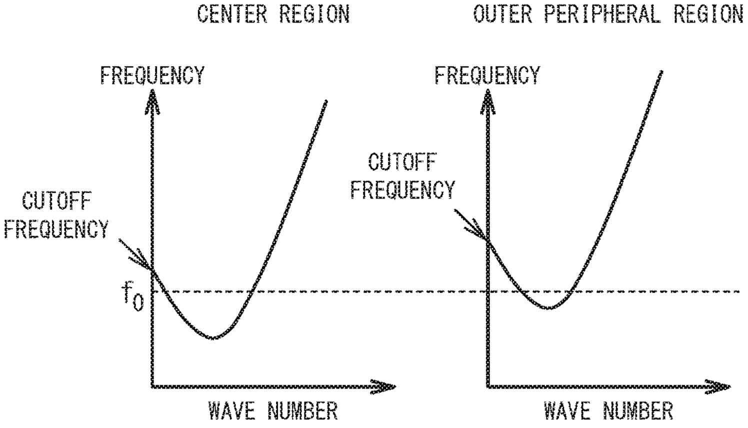

1000
68
68b
68a
68b
66
64
62
60
70
CUTOFF FREQUENCY

FIG. 3B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OUTER PERIPHERAL REGION
FREQUENCY
FREQUENCY
CUTOFF FREQUENCY
CUTOFF FREQUENCY
f_0
WAVE NUMBER
WAVE NUMBER

FIG. 4A

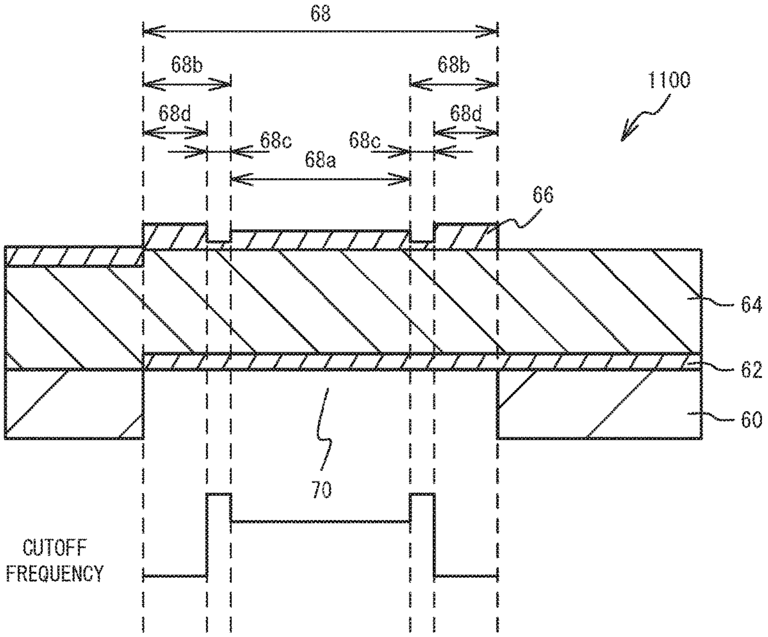

68
68b
68b
1100
68d
68d
68c
68c
68a
66
64
62
60
70
CUTOFF FREQUENCY

FIG. 4B

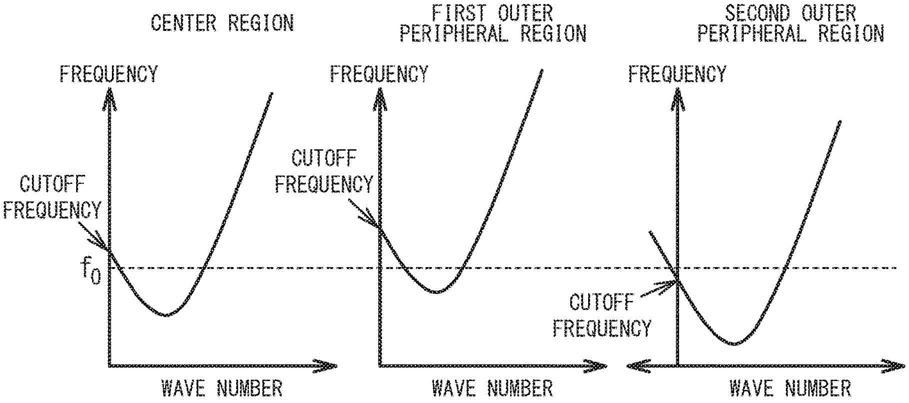

CENTER REGION
FIRST OUTER PERIPHERAL REGION
SECOND OUTER PERIPHERAL REGION
FREQUENCY
FREQUENCY
FREQUENCY
CUTOFF FREQUENCY
CUTOFF FREQUENCY
CUTOFF FREQUENCY
f_0
WAVE NUMBER
WAVE NUMBER
WAVE NUMBER

FIG. 5A

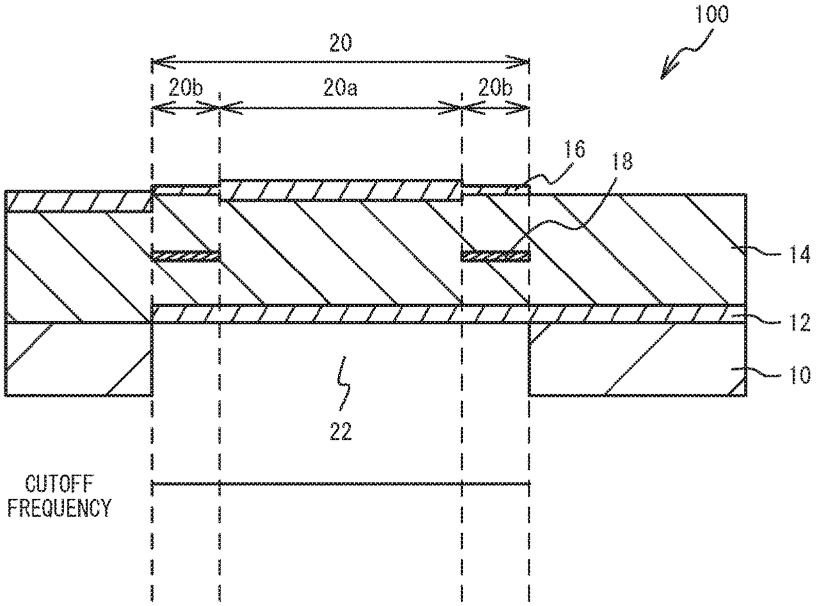

100
20
20b
20a
20b
16
18
14
12
10
22
CUTOFF FREQUENCY

FIG. 5B

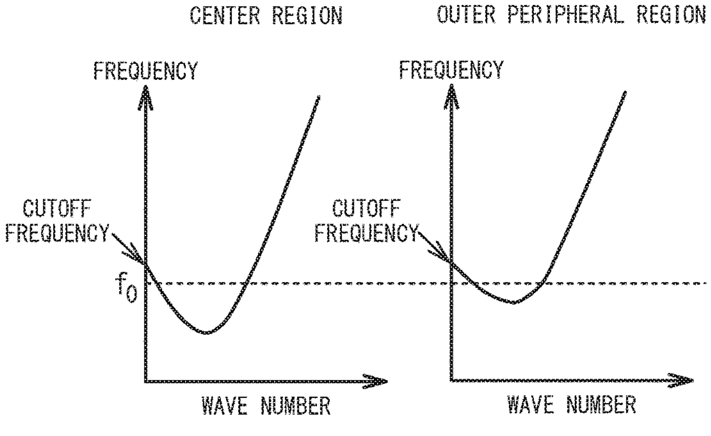

CENTER REGION
OUTER PERIPHERAL REGION
FREQUENCY
FREQUENCY
CUTOFF FREQUENCY
CUTOFF FREQUENCY
f_0
WAVE NUMBER
WAVE NUMBER

FIG. 6A

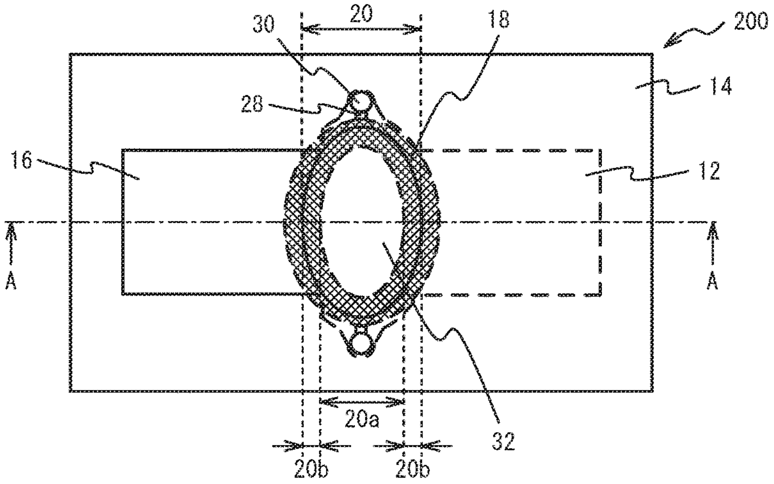


FIG. 6B

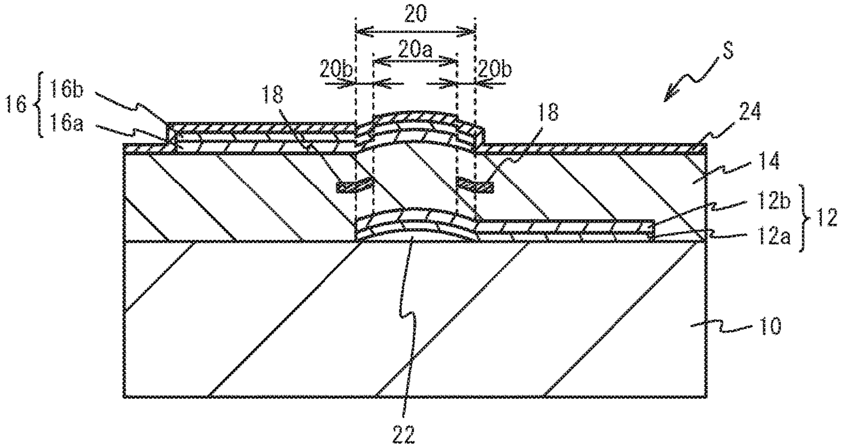


FIG. 6C

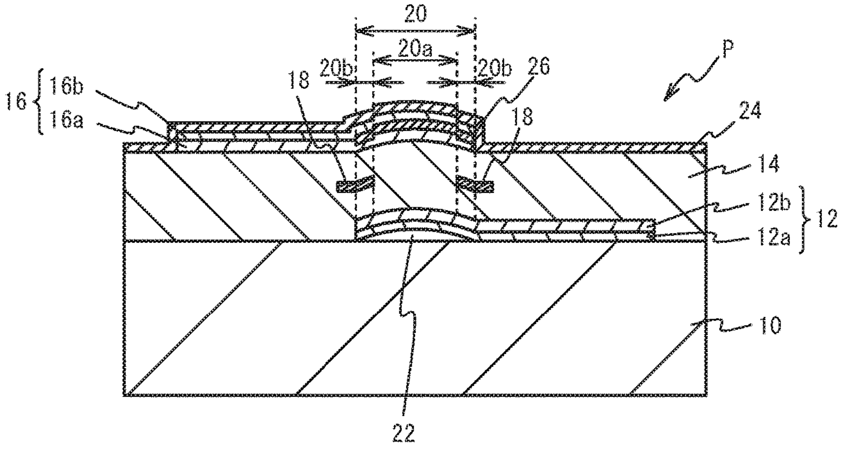


FIG. 7A

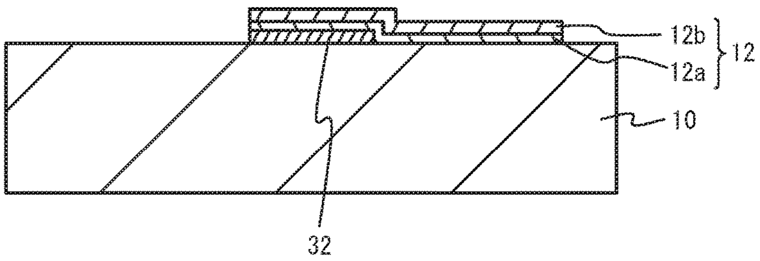


FIG. 7B

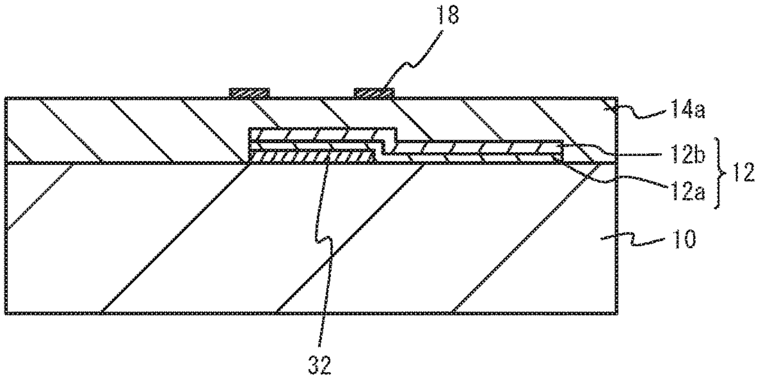


FIG. 7C

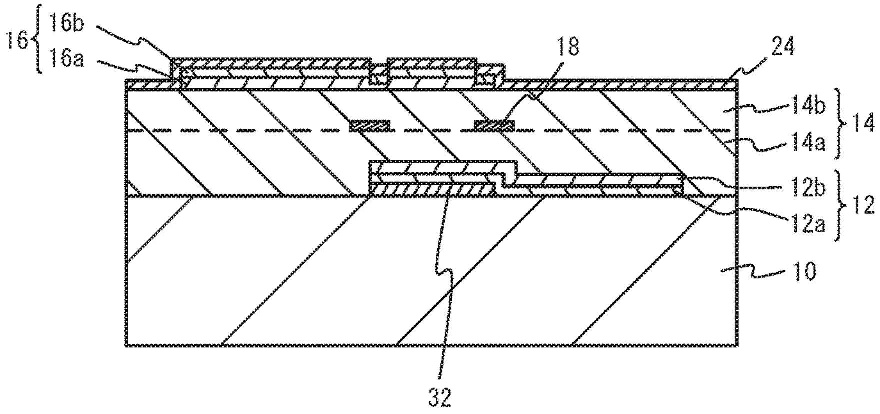
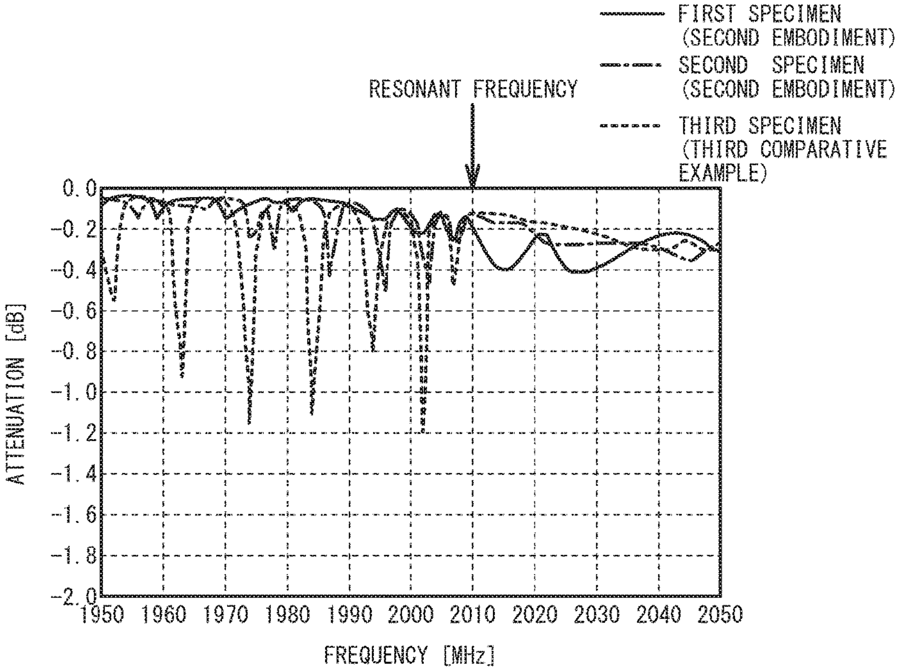


FIG. 8A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(SECOND EMBODIMENT)
SECOND SPECIMEN
(SECOND EMBODIMENT)
THIRD SPECIMEN
(THIRD COMPARATIVE
EXAMPLE)
RESONANT FREQUENCY
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
ATTENUATION [dB]
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
FREQUENCY [MHz]

FIG. 8B

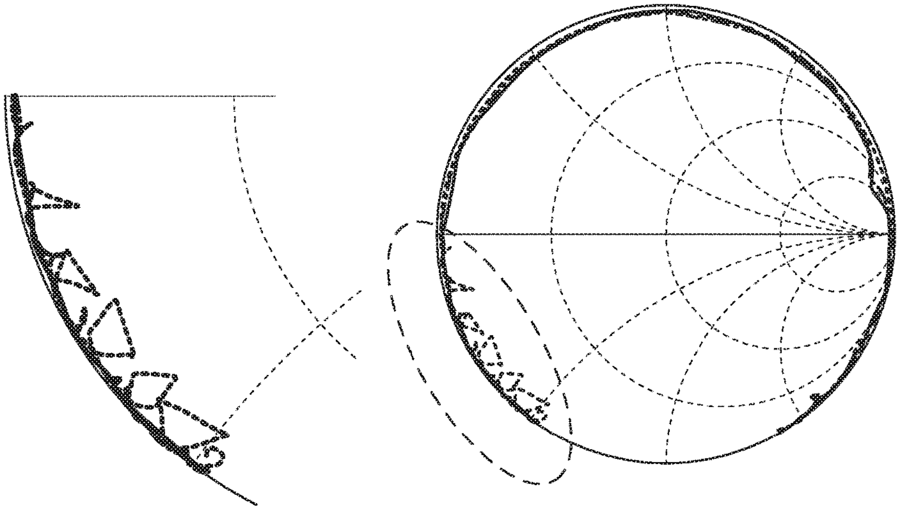
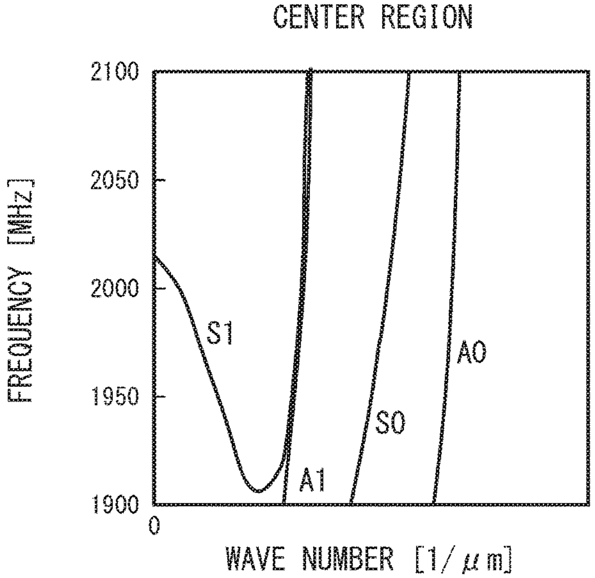


FIG. 9A


CENTER REGION
2100
2050
2000
1950
1900
0
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WAVE NUMBER [1/μm]
S1
A1
S0
A0

FIG. 9B

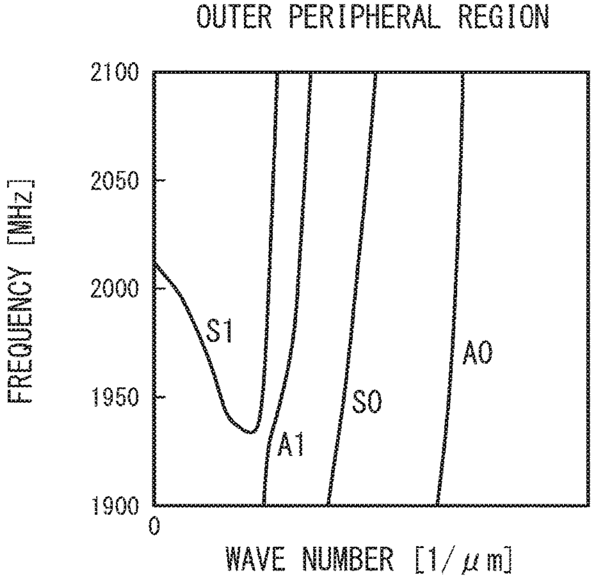
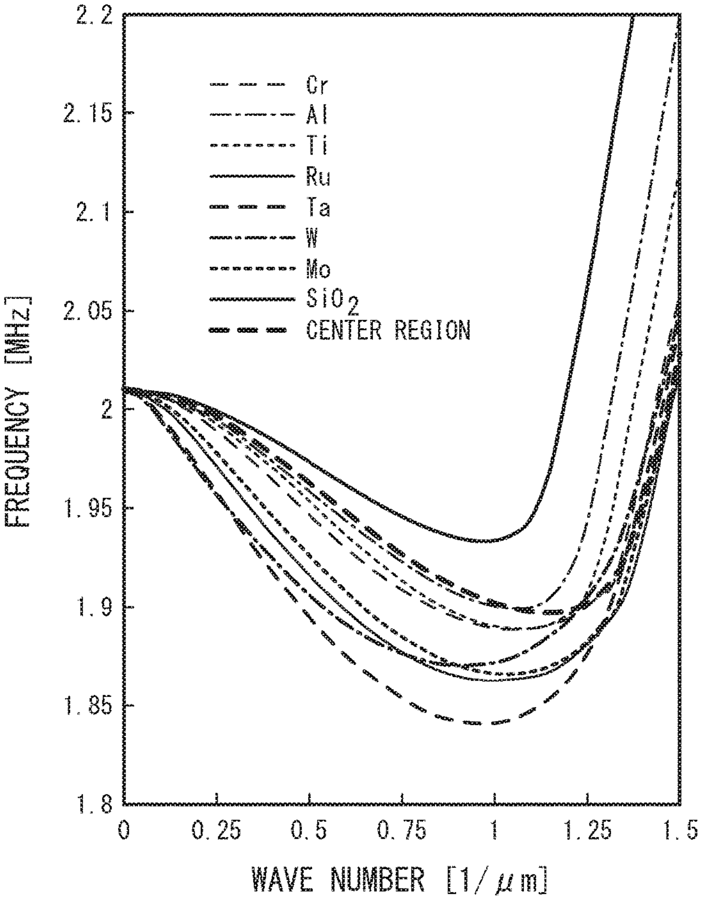

OUTER PERIPHERAL REGION
2100
2050
2000
1950
1900
0
FREQUENCY [MHz]
WAVE NUMBER [1/μm]
S1
A1
S0
A0

FIG. 10



2.2
2.15
2.1
2.05
2
1.95
1.9
1.85
1.8
FREQUENCY [MHz]
0
0.25
0.5
0.75
1
1.25
1.5
WAVE NUMBER [1/μm]
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Al
Ti
Ru
Ta
W
Mo
SiO2
CENTER REGION

FIG. 11A

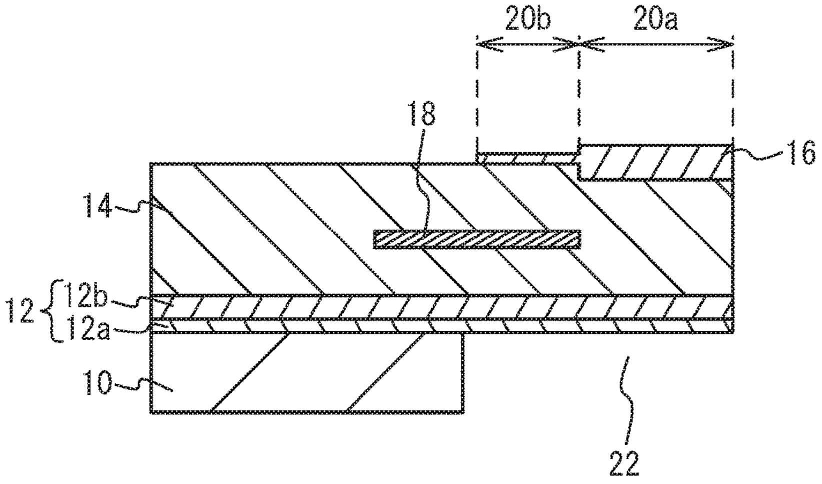


FIG. 11B

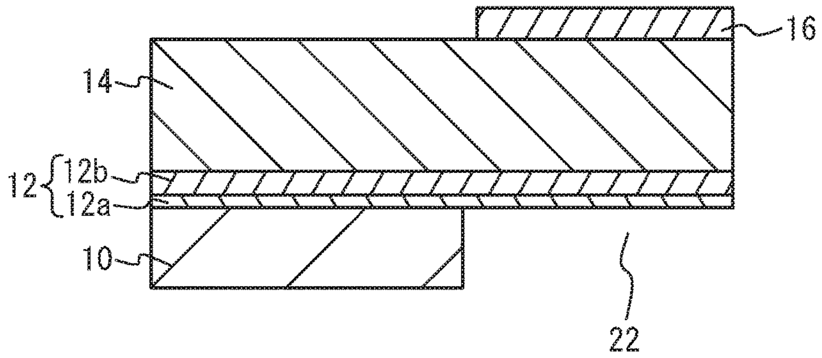


FIG. 12A

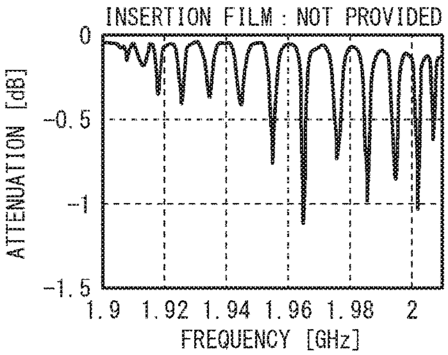


FIG. 12B

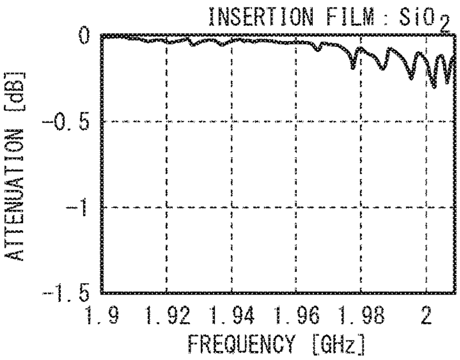


FIG. 12C

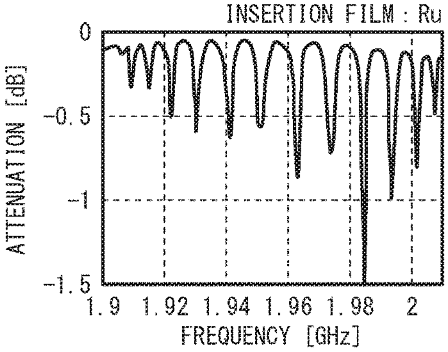


FIG. 12D

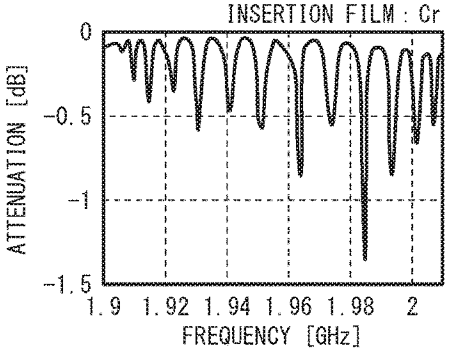


FIG. 12E

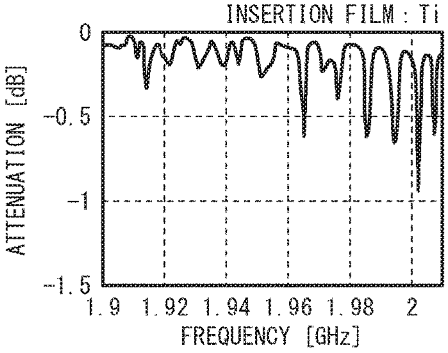


FIG. 12F

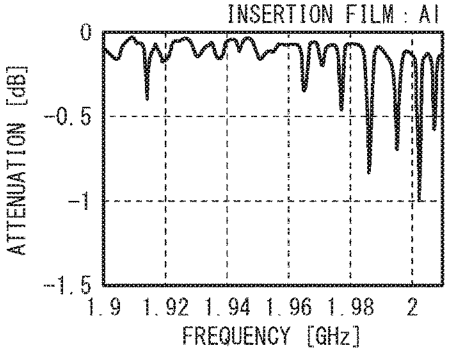


FIG. 13A

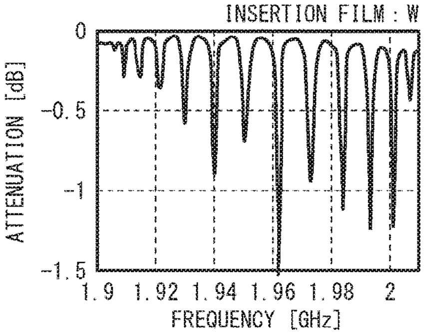


FIG. 13B

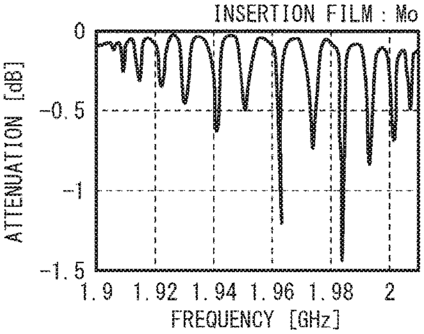


FIG. 13C

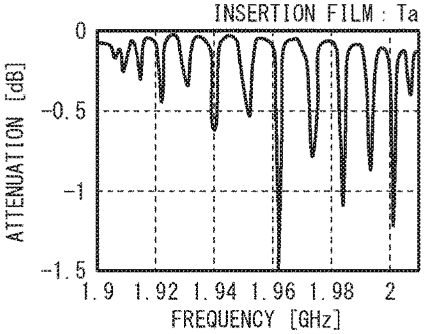


FIG. 14A

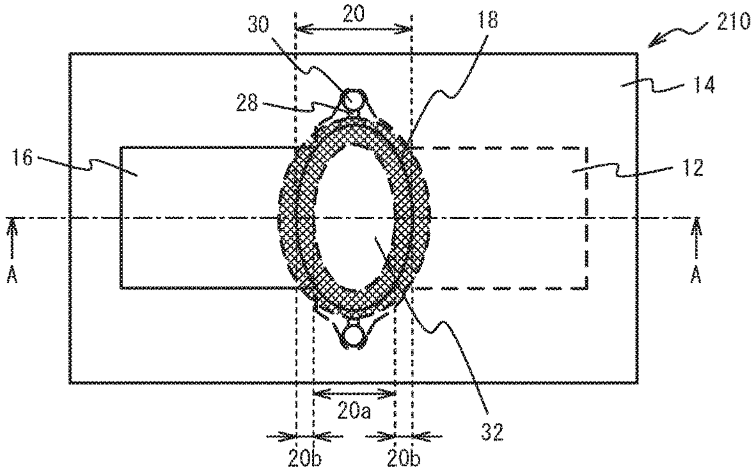


FIG. 14B

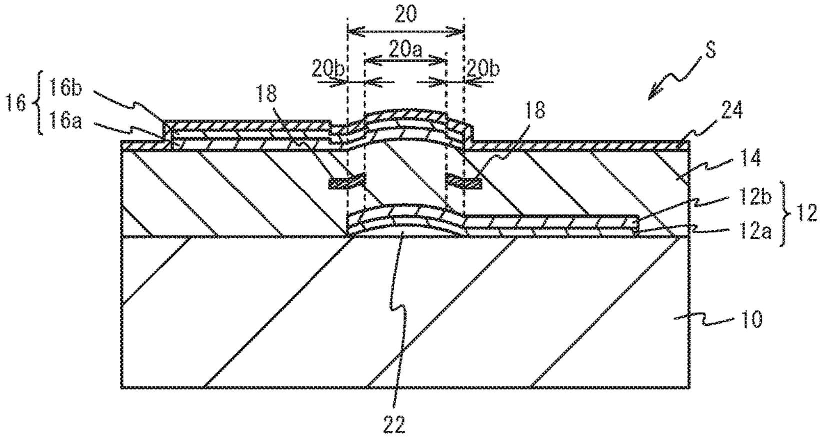


FIG. 15A

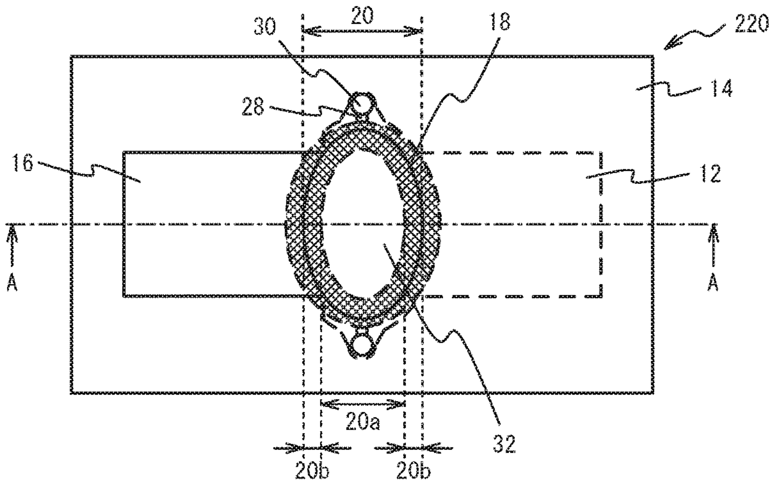


FIG. 15B

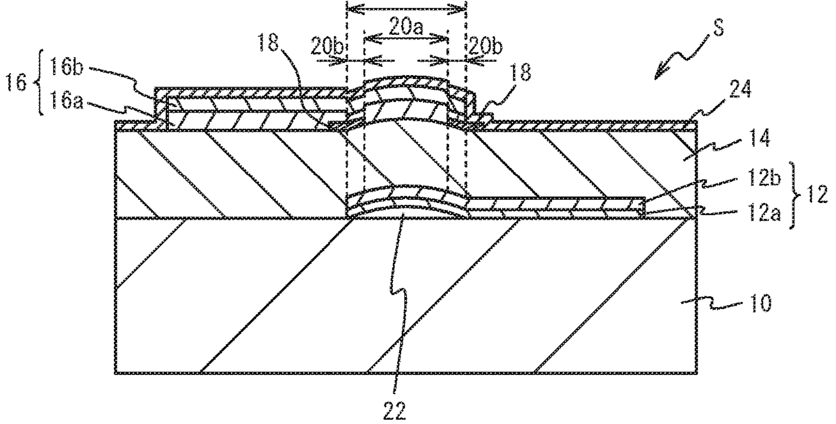


FIG. 16A

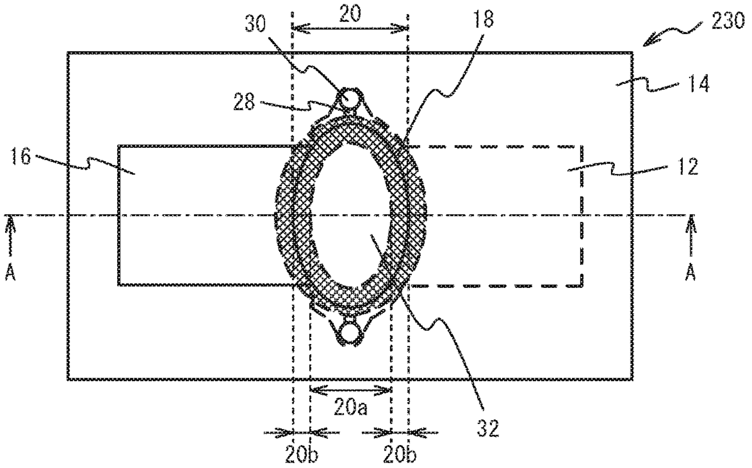


FIG. 16B

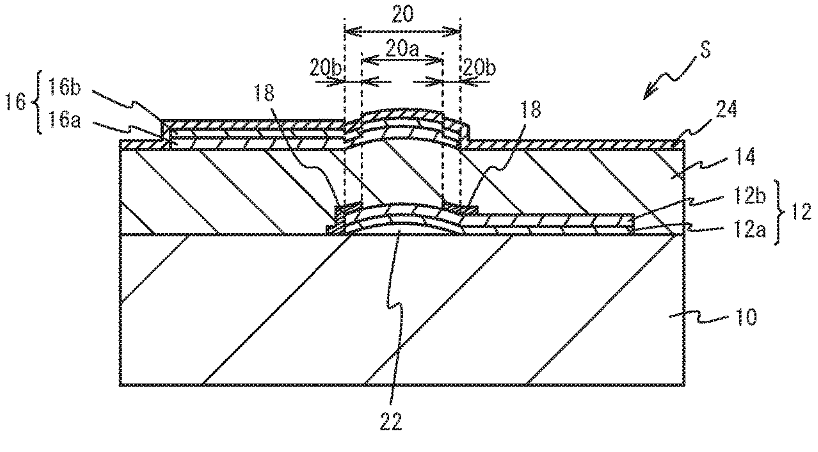


FIG. 17A

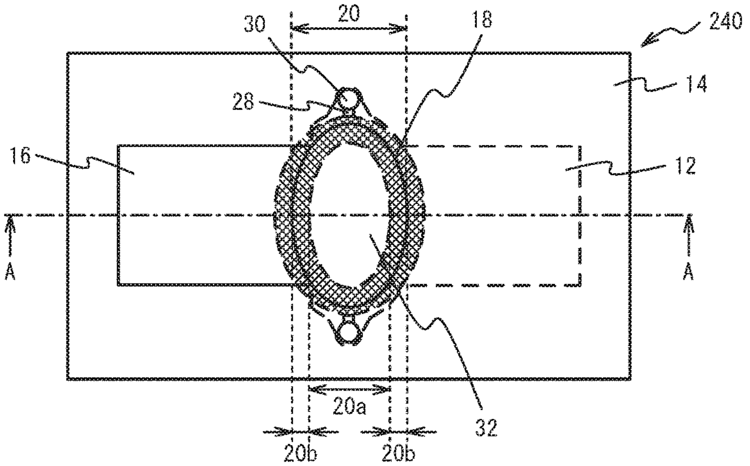


FIG. 17B

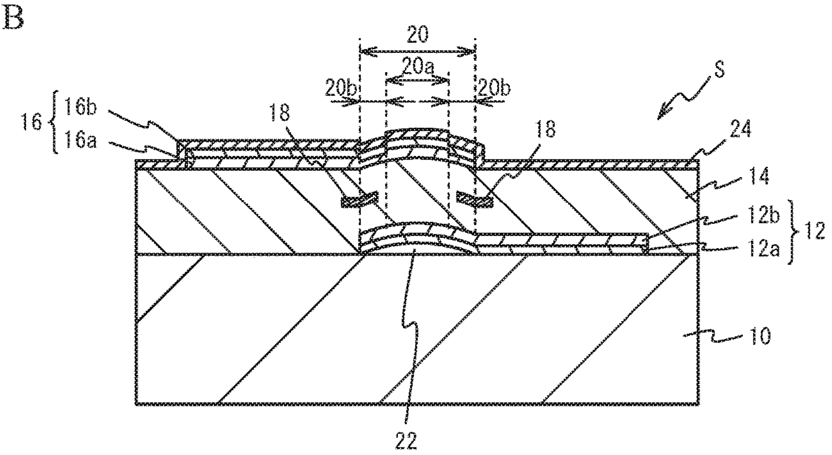


FIG. 18A

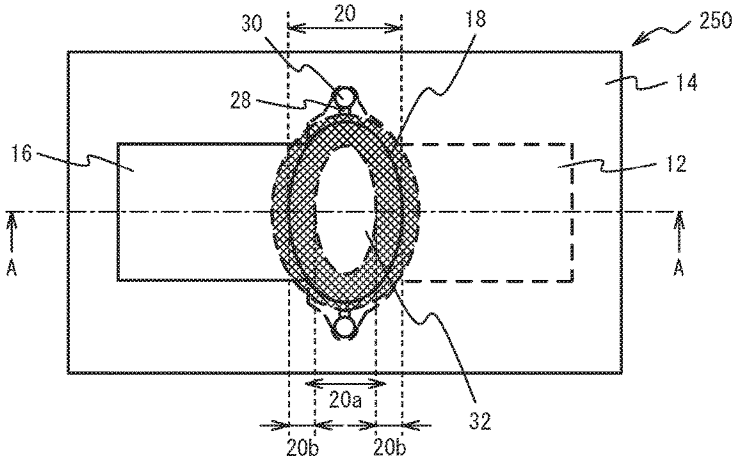


FIG. 18B

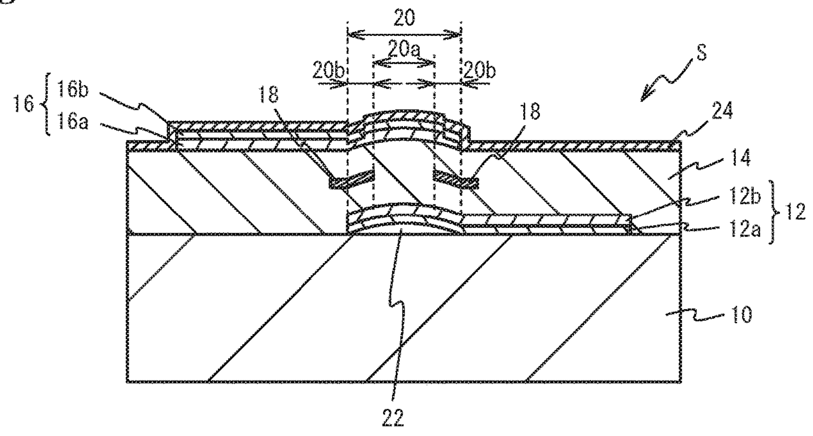


FIG. 19A

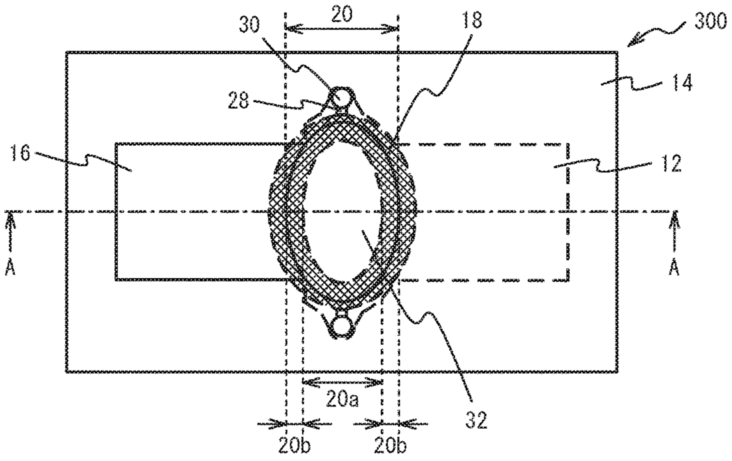


FIG. 19B

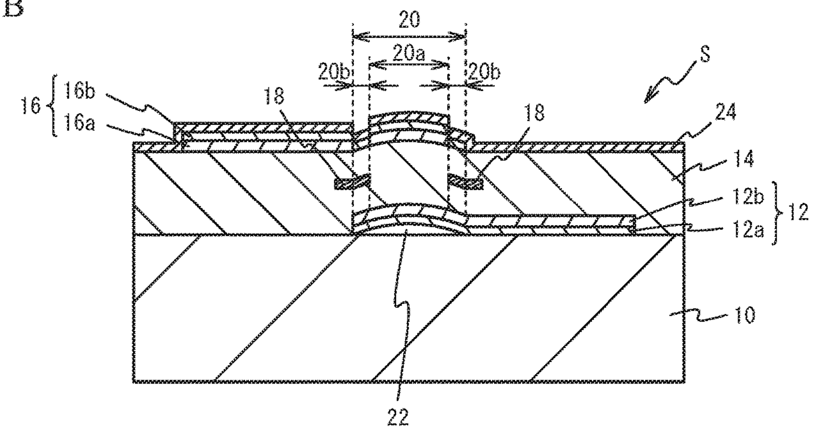


FIG. 20A

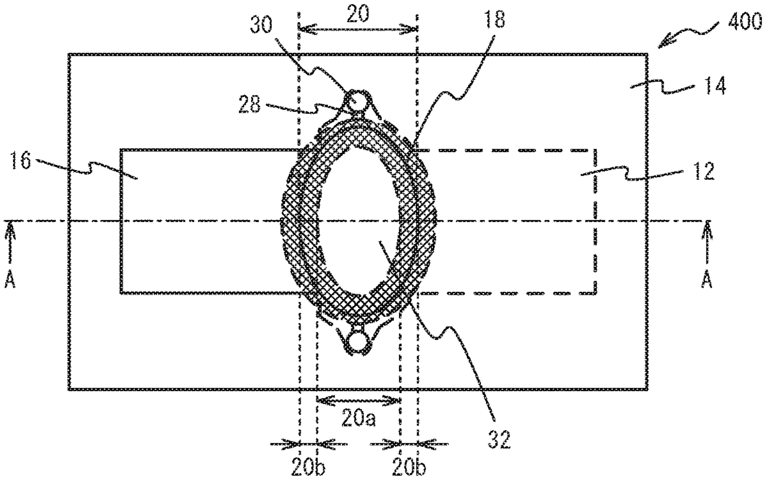


FIG. 20B

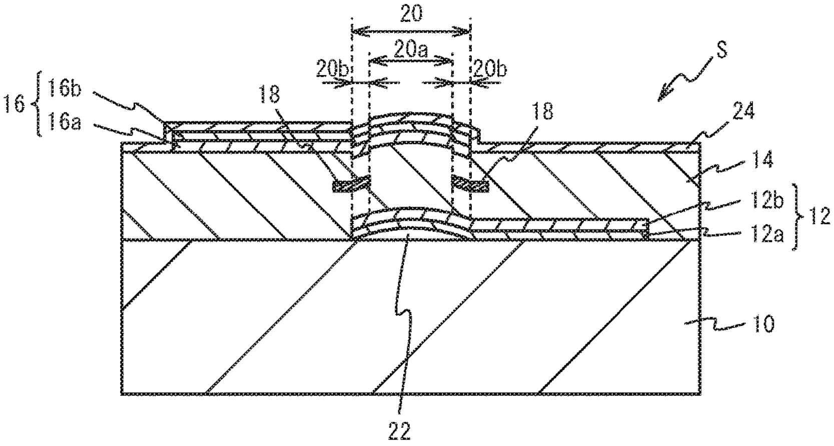


FIG. 21A

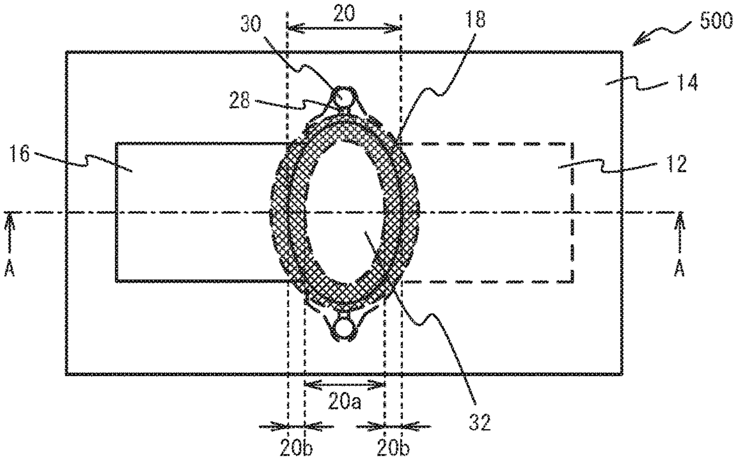


FIG. 21B

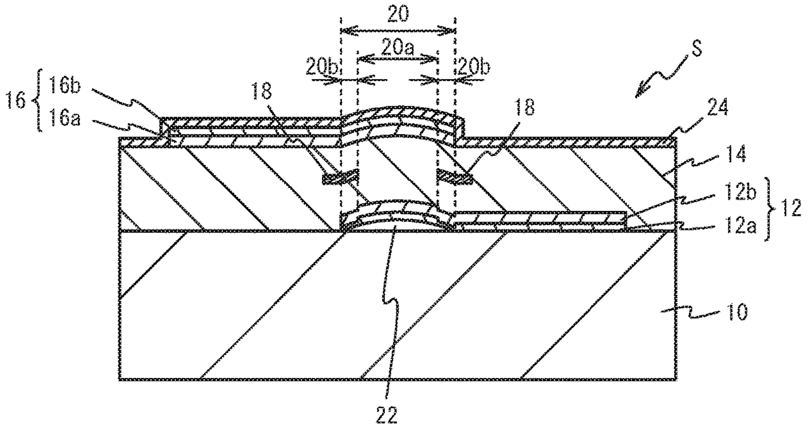


FIG. 22

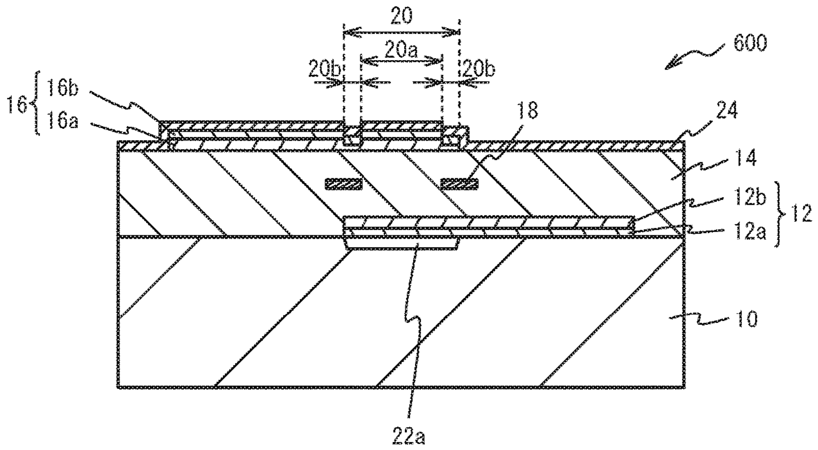


FIG. 23

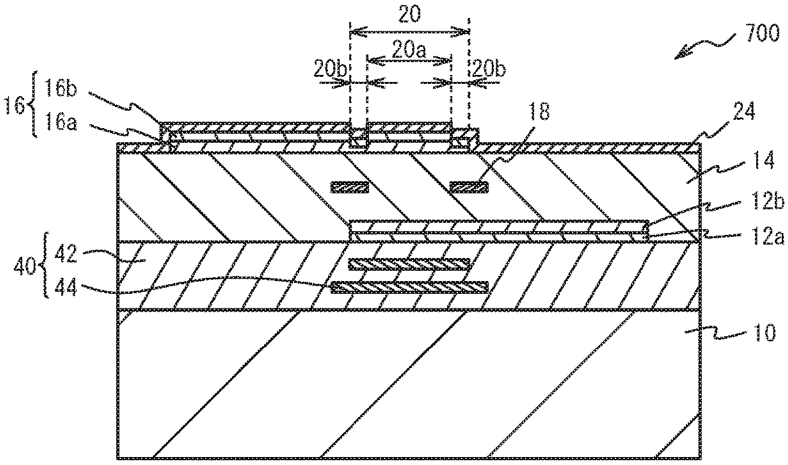


FIG. 24

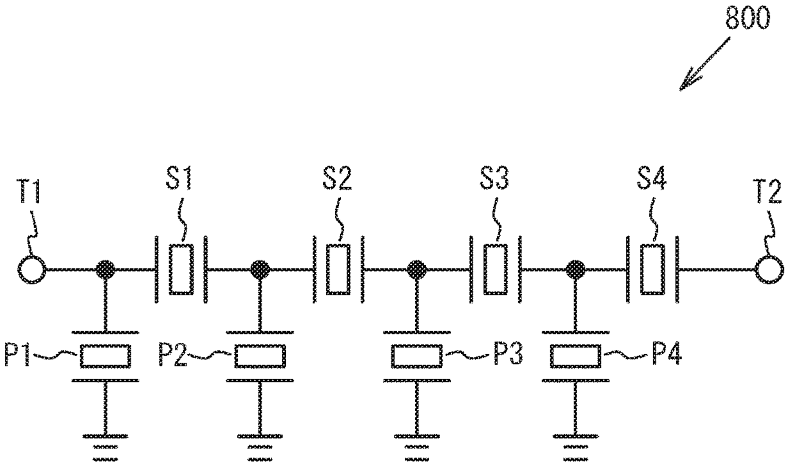
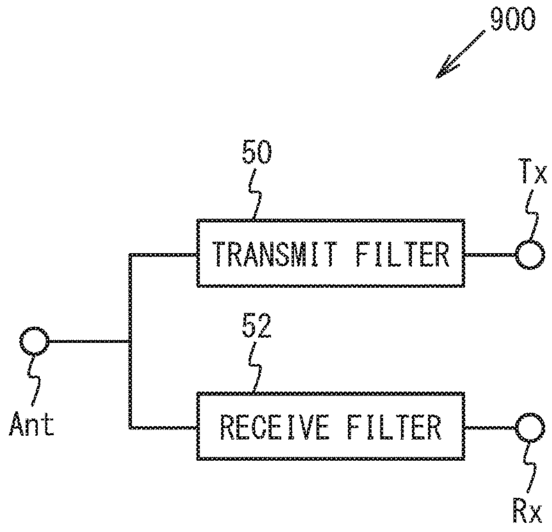


FIG. 25



PIEZOELECTRIC THIN FILM RESONATOR, FILTER, AND DUPLEXER

CROSS-REFERENCE TO RELATED APPLICATION

This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2015-150045, filed on Jul. 29, 2015, the entire contents of which are incorporated herein by reference.

FIELD

A certain aspect of the present invention relates to a piezoelectric thin film resonator, a filter, and a duplexer.

BACKGROUND

A piezoelectric thin film resonator, which is one of acoustic wave devices, has been used in a filter and a duplexer of wireless devices including mobile phones. The piezoelectric thin film resonator has a structure designed to have a lower electrode and an upper electrode facing each other across a piezoelectric film.

The piezoelectric thin film resonator collaterally generates waves propagating in the planar direction (the lateral direction) called the lateral mode in addition to the thickness extension mode that vibrates in the film thickness direction (the longitudinal direction) of the piezoelectric film. The wave propagating in the lateral direction is reflected by the edge portion of a resonance region. This causes spurious to occur in resonance characteristics. When the piezoelectric thin film resonator in which spurious has occurred is used in a filter, a large loss called a ripple occurs in the passband. Thus, there has been suggested various methods of reducing spurious as disclosed in, for example, Japanese Patent Application Publication Nos. 2003-505906, 2007-6501, and 2005-159402 and International Publication No. WO2006/129532. It has also been known that waves propagating through the piezoelectric film have many modes as disclosed in, for example, Ken L. Telschow, and another, “Determination of Lateral Mode Dispersion from Full-field Imaging of Film Bulk Acoustic Resonator Motion”, IEEE ULTRASONICS SYMPOSIUM, 2003, p. 280-283.

However, the conventional methods of reducing spurious deteriorate a Q-value or an electromechanical coupling coefficient.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a piezoelectric thin film resonator including: a substrate; a piezoelectric film that is located on the substrate and has a Poisson’s ratio of 0.33 or less; a lower electrode and an upper electrode that face each other across the piezoelectric film; and an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region, wherein at least one of the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region.

According to a second aspect of the present invention, there is provided a piezoelectric thin film resonator including: a substrate; a piezoelectric film that is located on the substrate and has a Poisson’s ratio of 0.33 or less; a lower electrode and an upper electrode that face each other across the piezoelectric film; and an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region, wherein a cutoff frequency in the outer peripheral region within the resonance region is approximately equal to a cutoff frequency in the center region of the resonance region, and a difference between the cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the outer peripheral region within the resonance region is less than a difference between the cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the center region of the resonance region.

According to a third aspect of the present invention, there is provided a filter including any one of the above piezoelectric thin film resonators.

According to a fourth aspect of the present invention, there is provided a duplexer including: a transmit filter; and a receive filter, wherein at least one of the transmit filter and the receive filter is the above filter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a dispersion relation k (ω) of a piezoelectric film;

FIG. 2 illustrates dispersion characteristics when the piezoelectric film is made of AlN within the range of a wave number k extended to a larger wave number;

FIG. 3A is a cross-sectional view of a piezoelectric thin film resonator in accordance with a first comparative example, and FIG. 3B illustrates dispersion curves of thickness extension modes in the center region and the outer peripheral region of a resonance region;

FIG. 4A is a cross-sectional view of a piezoelectric thin film resonator in accordance with a second comparative example, and FIG. 4B illustrates the dispersion curves of thickness extension modes in the center region, the first outer peripheral region, and the second outer peripheral region of the resonance region;

FIG. 5A is a cross-sectional view of a piezoelectric thin film resonator in accordance with a first embodiment, and FIG. 5B illustrates the dispersion curves of thickness extension modes in the center region and the outer peripheral region of the resonance region;

FIG. 6A is a top view of a piezoelectric thin film resonator in accordance with a second embodiment, and FIG. 6B and FIG. 6C are cross-sectional views taken along line A-A in FIG. 6A;

FIG. 7A through FIG. 7C are cross-sectional views illustrating a method of fabricating the piezoelectric thin film resonator of the second embodiment;

FIG. 8A and FIG. 8B illustrate the results of a simulation investigating spurious;

FIG. 9A and FIG. 9B illustrate the results of a simulation investigating a dispersion curve;

FIG. 10 illustrates the results of a simulation investigating the dispersion curves of thickness extension modes in the outer peripheral regions within the resonance regions of piezoelectric thin film resonators using different materials for an insertion film;

FIG. **11**A and FIG. **11**B are cross-sectional views of piezoelectric thin film resonators used for the simulation;

FIG. **12**A illustrates the results of a simulation of a reflection characteristic around the resonant frequency of a piezoelectric thin film resonator without the insertion film, and FIG. **12**B through FIG. **12**F are diagrams (No. **1**) illustrating the simulation results of the reflection characteristics around the resonant frequency of the piezoelectric thin film resonators using different materials for the insertion film;

FIG. **13**A through FIG. **13**C are diagrams (No. **2**) illustrating the simulation results of the reflection characteristics around the resonant frequency of the piezoelectric thin film resonators using different materials for the insertion film;

FIG. **14**A is a top view of a piezoelectric thin film resonator in accordance with a first variation of the second embodiment, and FIG. **14**B is a cross-sectional view taken along line A-A of FIG. **14**A;

FIG. **15**A is a top view of a piezoelectric thin film resonator in accordance with a second variation of the second embodiment, and FIG. **15**B is a cross-sectional view taken along line A-A of FIG. **15**A;

FIG. **16**A is a top view of a piezoelectric thin film resonator in accordance with a third variation of the second embodiment, and FIG. **16**B is a cross-sectional view taken along line A-A of FIG. **16**A;

FIG. **17**A is a top view of a piezoelectric thin film resonator in accordance with a fourth variation of the second embodiment, and FIG. **17**B is a cross-sectional view taken along line A-A of FIG. **17**A;

FIG. **18**A is a top view of a piezoelectric thin film resonator in accordance with a fifth variation of the second embodiment, and FIG. **18**B is a cross-sectional view taken along line A-A of FIG. **18**A;

FIG. **19**A is a top view of a piezoelectric thin film resonator in accordance with a third embodiment; and FIG. **19**B is a cross-sectional view taken along line A-A of FIG. **19**A;

FIG. **20**A is a top view of a piezoelectric thin film resonator in accordance with a fourth embodiment, and FIG. **20**B is a cross-sectional view taken along line A-A of FIG. **20**A;

FIG. **21**A is a top view of a piezoelectric thin film resonator in accordance with a fifth embodiment, and FIG. **21**B is a cross-sectional view taken along line A-A of FIG. **21**A;

FIG. **22** is a cross-sectional view of a piezoelectric thin film resonator in accordance with a sixth embodiment;

FIG. **23** is a cross-sectional view of a piezoelectric thin film resonator in accordance with a seventh embodiment;

FIG. **24** illustrates a filter in accordance with an eighth embodiment; and

FIG. **25** illustrates a duplexer in accordance with a ninth embodiment.

DETAILED DESCRIPTION

Hereinafter, embodiments of the present invention will be described with reference to the accompanying drawings.

First Embodiment

With FIG. **1**, the dispersion relation k (ω) of a piezoelectric film will be described. The vertical axis in FIG. **1**

represents angular frequency ω, the horizontal axis on the right to the vertical axis represents the real number of a wave number k, and the horizontal axis on the left to the vertical axis represents the imaginary number of the wave number k. When the wave number k is an imaginary number, the acoustic wave propagating through the piezoelectric film exponentially decays. The wave number k of 0 (zero) represents a cutoff frequency that is the resonant frequency of the thickness extension mode primarily contributing to the resonance of the piezoelectric thin film resonator. As illustrated in FIG. **1**, when the piezoelectric film is made of a Type I material with a Poisson's ratio greater than 0.33, the lateral mode collaterally generated in addition to the thickness extension mode is at a frequency greater than the cutoff frequency. The type I material is, for example, zinc oxide (ZnO). In contrast, when the piezoelectric film is made of a Type II material with a Poisson's ratio of 0.33 or less, the lateral mode is generated at a frequency less than the cutoff frequency. The type II material is, for example, aluminum nitride (AlN).

FIG. **1** illustrates only the area where the wave number k of the dispersion curve of the thickness extension mode **S1** primarily contributing to the resonance of the piezoelectric thin film resonator is small. FIG. **2** illustrates the dispersion characteristics when the piezoelectric film is made of AlN within the range of the real number of the wave number k extended to a larger real number. As illustrated in FIG. **2**, in the dispersion curve of the mode S**1**, the frequency monotonically decreases till the wave number reaches k**1**, and the frequency monotonically increases after the wave number exceeds k**1**. In addition to the mode S**1**, many modes such as the mode S**0**, the mode A**1**, and the mode A**0** exist. The mode A**0** is the base mode of an asymmetric mode. The mode S**0** is the base mode of a symmetric mode. The mode A**1** is the first-order mode of the asymmetric mode. The mode S**1** is a primary mode that primarily contributes to the resonance of the piezoelectric thin film resonator as described above.

FIG. **3**A is a cross-sectional view of a piezoelectric thin film resonator **1000** in accordance with a first comparative example, and FIG. **3**B illustrates the dispersion curves of the thickness extension modes in a center region **68***a* and an outer peripheral region **68***b* of a resonance region **68**. As illustrated in FIG. **3**A, the piezoelectric thin film resonator **1000** of the first comparative example includes a lower electrode **62** formed on a substrate **60**. A piezoelectric film **64** made of AlN is formed on the substrate **60** and the lower electrode **62**. An upper electrode **66** is formed on the piezoelectric film **64** so as to have a region (the resonance region **68**) in which the upper electrode **66** faces the lower electrode **62** across the piezoelectric film **64**. The resonance region **68** is a region in which the thickness extension mode resonates. An air gap **70** is formed in a region, including the resonance region **68**, of the substrate **60**.

The upper electrode **66** in the outer peripheral region **68***b* within the resonance region **68** is thinner than the upper electrode **66** in the center region **68***a* of the resonance region **68**. Thus, the cutoff frequency in the outer peripheral region **68***b* is greater than the cutoff frequency in the center region **68***a*.

As illustrated in FIG. **3**B, since the cutoff frequency in the outer peripheral region **68***b* is greater than the cutoff frequency in the center region **68***a*, the dispersion curve of the mode **S1** in the outer peripheral region **68***b* shifts to a frequency greater than that of the dispersion curve of the mode **S1** in the center region **68***a*. Thus, the real number of the wave number at a frequency f**0**, which is less than the resonant frequency in the center region **68***a*, has a value greater in the outer peripheral region **68***b* than in the center region **68***a*. Accordingly, the acoustic wave that has a frequency less than the resonant frequency in the center region **68***a* and propagates in the lateral direction leaks from the center region **68***a* to the outside more easily. This reduces the occurrence of spurious due to the lateral mode in the resonance characteristics. However, since the acoustic wave leaks from the center region **68***a* to the outside, the Q-value decreases across a wide range from the resonant frequency to the antiresonant frequency.

FIG. **4**A is a cross-sectional view of a piezoelectric thin film resonator **1100** in accordance with a second comparative example, and FIG. **4**B illustrates the dispersion curves of the thickness extension modes in the center region **68***a*, a first outer peripheral region **68***c*, and a second outer peripheral region **68***d* of the resonance region **68**. As illustrated in FIG. **4**A, in the piezoelectric thin film resonator **1100** of the second comparative example, the outer peripheral region **68***b* within the resonance region **68** includes the first outer peripheral region **68***c* in which the upper electrode **66** is thinner than in the center region **68***a*, and the second outer peripheral region **68***d* in which the upper electrode **66** is thicker than in the center region **68***a*. Thus, the cutoff frequency in the first outer peripheral region **68***c* is greater than the cutoff frequency in the center region **68***a*. The cutoff frequency in the second outer peripheral region **68***d* is less than the cutoff frequency in the center region **68***a*.

As illustrated in FIG. **4**B, as the cutoff frequency in the first outer peripheral region **68***c* is greater than the cutoff frequency in the center region **68***a*, the dispersion curve of the mode S1 in the first outer peripheral region **68***c* shifts to a frequency greater than that of the dispersion curve of the mode S1 in the center region **68***a*. As the cutoff frequency in the second outer peripheral region **68***d* is less than the cutoff frequency in the center region **68***a*, the dispersion curve of the mode S1 in the second outer peripheral region **68***d* shifts to a frequency less than that of the dispersion curve of the mode S1 in the center region **68***a*. Accordingly, the wave number at the frequency f**0**, which is less than the resonant frequency in the center region **68***a*, takes a real number of which the value is greater in the first outer peripheral region **68***c* than in the center region **68***a*, and takes an imaginary number in the second outer peripheral region **68***d*. Therefore, the acoustic wave having a frequency less than the resonant frequency in the center region **68***a* and propagating in the lateral direction leaks from the center region **68***a* to the first outer peripheral region **68***c* more easily, and is inhibited from leaking in the second outer peripheral region **68***d*. As the acoustic wave propagating in the lateral direction leaks to the first outer peripheral region **68***c* more easily, the occurrence of spurious due to the lateral mode is reduced in the resonance characteristics, and as the acoustic wave propagating in the lateral direction is reflected by the second outer peripheral region **68***d*, the degradation of the Q-value between the resonant frequency and the antiresonant frequency is inhibited. However, the provision of both the first outer peripheral region **68***c* with a high cutoff frequency and the second outer peripheral region **68***d* with a low cutoff frequency decreases the area of the center region **68***a*, causing an electromechanical coupling coefficient k2 to decrease.

FIG. **5**A is a cross-sectional view of a piezoelectric thin film resonator **100** in accordance with a first embodiment, and FIG. **5**B illustrates the dispersion curves of the thickness extension modes in a center region **20***a* and an outer peripheral region **20***b* of a resonance region **20**. As illustrated in FIG. **5**A, the piezoelectric thin film resonator **100** of the first embodiment includes a lower electrode **12** formed on a substrate **10** made of, for example, a silicon (Si) substrate. The lower electrode **12** is formed of a metal film such as, for example, a chrome (Cr) film or a ruthenium (Ru) film. A piezoelectric film **14** with a Poisson's ratio of 0.33 or less is formed on the substrate **10** and the lower electrode **12**. The piezoelectric film **14** is formed of, for example, AlN. An upper electrode **16** is formed on the piezoelectric film **14** so as to have a region (the resonance region **20**) in which the upper electrode **16** faces the lower electrode **12** across the piezoelectric film **14**. The upper electrode **16** is formed of a metal film such as, for example, a Cr film or a Ru film. The resonance region **20** is a region in which the thickness extension mode resonates. An air gap **22** is formed in a region, including the resonance region **20**, of the substrate **10**.

In the piezoelectric film **14**, an insertion film **18** is formed in the outer peripheral region **20***b* within the resonance region **20**. The insertion film **18** is not formed in the center region **20***a* of the resonance region **20**. The insertion film **18** is made of, for example, a silicon dioxide (SiO_2) film. The outer peripheral region **20***b* within the resonance region **20** is a region that is located within the resonance region **20**, includes the outer periphery of the resonance region **20**, and is located along the outer periphery. The center region **20***a* of the resonance region **20** is a region that is located within the resonance region **20**, is located further in than the outer peripheral region **20***b*, and includes the center of the resonance region **20**.

The upper electrode **16** in the outer peripheral region **20***b* is thinner than the upper electrode **16** in the center region **20***a*. Thus, the thickness of the multilayered film including the lower electrode **12**, the piezoelectric film **14**, the insertion film **18**, and the upper electrode **16** in the resonance region **20** is less in the outer peripheral region **20***b* than in the center region **20***a*. Since the insertion film **18** is formed in the outer peripheral region **20***b*, and the upper electrode **16** in the outer peripheral region **20***b* is configured to be thinner, the cutoff frequency in the center region **20***a* is equal to or approximately equal to the cutoff frequency in the outer peripheral region **20***b*.

As illustrated in FIG. **5**B, the dispersion curve of the mode S1 in the center region **20***a* has a different shape from that in the outer peripheral region **20***b*. The dispersion curve of the mode S1 in the outer peripheral region **20***b* has a larger curvature around the minimum frequency than the dispersion curve of the mode S1 in the center region **20***a*. This is because the insertion film **18** is formed in the piezoelectric film **14** in the outer peripheral region **20***b*, and thus the material sandwiched between the lower and upper electrodes **12** and **16** has different Poisson's ratios between the center region **20***a* and the outer peripheral region **20***b*.

The control of the shapes of the dispersion curves of the mode S1 in the center region **20***a* and the outer peripheral region **20***b* allows the value of the real number of the wave number at the frequency f**0**, which is less than the resonant frequency in the center region **20***a*, to be greater in the outer peripheral region **20***b* than in the center region **20***a*. In other words, the control of the frequency at which the slope of the dispersion curve of the mode S1 is zero allows the value of the real number of the wave number at the frequency f**0**, which is less than the resonant frequency in the center region **20***a*, to be greater in the outer peripheral region **20***b* than in the center region **20***a*. Accordingly, the acoustic wave having a frequency less than the resonant frequency in the center region **20***a* and propagating in the lateral direction leaks from the center region **20***a* to the outside more easily, and the occurrence of spurious due to the lateral mode is inhibited in the resonance characteristics. In addition, the provision of the insertion film **18** reduces the generation of the acoustic wave in the mode S**0** between the resonant frequency and the antiresonant frequency. As the generation of the acoustic wave in the mode S**0** itself is reduced, the leakage of the acoustic wave is also reduced. As a result, the degradation of the Q-value between the resonant frequency and the anti-resonant frequency is inhibited. Additionally, as the cutoff frequency in the center region **20***a* can be made equal to or approximately equal to the cutoff frequency in the outer peripheral region **20***b*, the degradation of the electromechanical coupling coefficient k2 is inhibited.

As described above, in the first embodiment, as illustrated in FIG. **5**A, the insertion film **18** is located in the outer peripheral region **20***b* within the resonance region **20**, and the thickness of the upper electrode **16** is less in the outer peripheral region **20***b* than in the center region **20***a*. This configuration makes the cutoff frequency in the outer peripheral region **20***b* approximately equal to the cutoff frequency in the center region **20***a*, and makes the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the outer peripheral region **20***b* less than the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the center region **20***a* as illustrated in FIG. **5**A and FIG. **5**B. Thus, as described above, the degradation of the Q-value and the electromechanical coupling coefficient k2 is inhibited, and spurious is reduced. A case where the cutoff frequencies are approximately equal to each other includes not only a case where the cutoff frequencies are completely identical but also a case where the cutoff frequencies are identical to the extent that the degradation of the electromechanical coupling coefficient k2 is inhibited.

Second Embodiment

FIG. **6**A is a top view of a piezoelectric thin film resonator **200** in accordance with a second embodiment, and FIG. **6**B and FIG. **6**C are cross-sectional views taken along line A-A of FIG. **6**A. FIG. **6**B is a cross-sectional view of a series resonator S of a ladder-type filter, and FIG. **6**C is a cross-sectional view of a parallel resonator P of the ladder-type filter.

As illustrated in FIG. **6**A and FIG. **6**B, the series resonator S includes the lower electrode **12** formed on the substrate **10**. The air gap **22** having a dome-shaped bulge toward the lower electrode **12** is formed between the flat principal surface of the substrate **10** and the lower electrode **12**. The dome-shaped bulge is a bulge having a shape with which the height of the air gap **22** is low near the periphery of the air gap **22** and the height of the air gap **22** increases at closer distances to the center of the air gap **22**, for example. The lower electrode **12** includes a lower layer **12***a* and an upper layer **12***b*. The lower layer **12***a* is made of, for example, a Cr film, and the upper layer **12***b* is made of, for example, a Ru film.

Formed on the substrate **10** and the lower electrode **12** is the piezoelectric film **14** mainly composed of AlN having the (**002**) direction as a main axis. The upper electrode **16** is formed on the piezoelectric film **14** so as to have a region (the resonance region **20**) in which the upper electrode **16** faces the lower electrode **12** across the piezoelectric film **14**. The upper electrode **16** includes a lower layer **16***a* and an upper layer **16***b*. The lower layer **16***a* is made of, for example, a Ru film, and the upper layer **16***b* is made of, for example, a Cr film. The resonance region **20** is a region having, for example, an elliptical shape, and in which the thickness extension mode resonates.

In the piezoelectric film **14**, the insertion film **18** is formed in the outer peripheral region **20***b* within the resonance region **20**. The insertion film **18** is not formed in the center region **20***a* of the resonance region **20**. The insertion film **18** is made of, for example, a SiO_2 film. The insertion film **18** is formed in the entire periphery of the outer peripheral region **20***b* within the resonance region **20**, and is formed to extend from the outer peripheral region **20***b* to the outside of the resonance region **20**. The insertion film **18** may be formed in the middle part in the film thickness direction of the piezoelectric film **14**, or may be formed in other than the middle part. As described in the first embodiment, the outer peripheral region **20***b* is a region that is located within the resonance region **20**, includes the outer periphery of the resonance region **20**, and is located along the outer periphery. The outer peripheral region **20***b* has, for example, a ring shape. The center region **20***a* of the resonance region **20** is a region that is located within the resonance region **20**, located further in than the outer peripheral region **20***b*, and includes the center of the resonance region **20**.

The upper electrode **16** in the outer peripheral region **20***b* is thinner than the upper electrode **16** in the center region **20***a* across the entire periphery of the outer peripheral region **20***b*. For example, the thickness of the lower layer **16***a* of the upper electrode **16** is less in the outer peripheral region **20***b* than in the center region **20***a*, and the thickness of the upper layer **16***b* of the upper electrode **16** is the same between the center region **20***a* and the outer peripheral region **20***b*. A silicon oxide film as a frequency adjusting film **24** is formed on the upper electrode **16**. The frequency adjusting film **24** may act as a passivation film. As the upper electrode **16** is thinner in the outer peripheral region **20***b* than in the center region **20***a*, the thickness of the multilayered film including the lower electrode **12**, the piezoelectric film **14**, the insertion film **18**, the upper electrode **16**, and the frequency adjusting film **24** in the resonance region **20** is less in the outer peripheral region **20***b* than in the center region **20***a*.

An introduction path **28** used to etch a sacrifice layer is formed in the lower electrode **12** and the piezoelectric film **14**. The sacrifice layer is used to form the air gap **22**. The vicinity of the tip of the introduction path **28** is not covered with the lower electrode **12** or the piezoelectric film **14**, and includes a hole portion **30** formed therein.

As illustrated in FIG. **6**A and FIG. **6**C, compared to the series resonator S, the parallel resonator P includes a mass load film **26** formed between the lower and upper layers **16***a* and **16***b* of the upper electrode **16** in the resonance region **20**. The mass load film **26** is made of, for example, a titanium (Ti) film. Other configurations are the same as those of the series resonator S, and thus the description is omitted.

The difference in the resonant frequency between the series and parallel resonators S and P is adjusted with the film thickness of the mass load film **26**. The resonant frequency of each of the series and parallel resonators S and P is adjusted with the film thickness of the corresponding frequency adjusting film **24**.

For example, when the piezoelectric thin film resonator has a resonant frequency of 2 GHz, the lower layer **12***a* made of a Cr film in the lower electrode **12** has a thickness of 100 nm, and the upper layer **12***b* made of a Ru film has a thickness of 250 nm. The piezoelectric film **14** made of an AlN film has a thickness of 1100 nm, and the insertion film **18** in the piezoelectric film **14** has a thickness of 150 nm.

The lower layer **16***a* made of a Ru film in the upper electrode **16** has a thickness of 230 nm in the center region **20***a* of the resonance region **20** and 50 nm in the outer peripheral region **20***b*. The upper layer **16***b* made of a Cr film in the upper electrode **16** has a thickness of 50 nm. The frequency adjusting film **24** made of a silicon oxide film has a thickness of 50 nm. The mass load film **26** made of a Ti film has a thickness of 120 nm. The thickness of each layer is appropriately designed to obtain desired resonance characteristics.

The substrate **10** may be, for example, a quartz substrate, a glass substrate, a ceramic substrate, or a gallium arsenide (GaAs) substrate instead of a Si substrate. The lower electrode **12** and the upper electrode **16** may be made of a single layer film of, for example, aluminum (Al), titanium (Ti), copper (Cu), molybdenum (Mo), tungsten (W), tantalum (Ta), platinum (Pt), rhodium (Rh), or iridium (Ir), or a multilayered film of at least two of them instead of Cr and Ru. The piezoelectric film **14** may be made of a material other than AlN as long as the material has a Poisson's ratio of 0.33 or less. The piezoelectric film **14** may be mainly composed of AlN and include other elements to improve the resonance characteristics or the piezoelectricity. For example, the use of scandium (Sc) as an additive element improves the piezoelectricity of the piezoelectric film **14**.

The frequency adjusting film **24** may be made of a silicon nitride film or an aluminum nitride film instead of a silicon oxide film. The mass load film **26** may be made of a single layer metal film of Ru, Cr, Al, Cu, Mo, W, Ta, Pt, Rh, or Ir, or a multilayered film of at least two of them instead of Ti. Alternatively, metal nitride such as, for example, silicon nitride or silicon oxide or an insulating film made of metal oxide may be used. The mass load film **26** may be formed, for example, below the lower electrode **12**, between the layers of the lower electrode **12**, on the upper electrode **16**, between the lower electrode **12** and the piezoelectric film **14**, or between the piezoelectric film **14** and the upper electrode **16** instead of between the layers of the upper electrode **16**. The mass load film **26** may be larger than the resonance region **20** as long as the mass load film **26** includes the resonance region **20**.

A method of fabricating the piezoelectric thin film resonator **200** of the second embodiment will be described by using the series resonator S as an example. FIG. **7**A through FIG. **7**C are cross-sectional views illustrating the method of fabricating the piezoelectric thin film resonator **200** of the second embodiment. As illustrated in FIG. **7**A, a sacrifice layer **32** used to form the air gap **22** is formed on the flat principal surface of the substrate **10**. The sacrifice layer **32** is formed by, for example, sputtering, vacuum evaporation, or Chemical Vapor Deposition (CVD). The sacrifice layer **32** may be made of a material such as, for example, magnesium oxide (MgO), zinc oxide (ZnO), germanium (Ge), or silicon dioxide (SiO_2) that easily dissolves in an etching liquid or an etching gas. The sacrifice layer **32** has a thickness of, for example, approximately 10 to 100 nm. Then, the sacrifice layer **32** is patterned into a desired shape by photolithography and etching. The shape of the sacrifice layer **32** corresponds to the planar shape of the air gap **22**, and includes, for example, a region to be the resonance region **20**.

Then, the lower and upper layers **12***a* and **12***b* are formed, as the lower electrode **12**, on the sacrifice layer **32** and the substrate **10**. The lower electrode **12** is formed by, for example, sputtering, vacuum evaporation, or CVD. Then, the lower electrode **12** is patterned into a desired shape by photolithography and etching. The lower electrode **12** may be formed by liftoff.

As illustrated in FIG. **7**B, a first piezoelectric film **14***a* and the insertion film **18** are formed on the lower electrode **12** and the substrate **10**. The first piezoelectric film **14***a* and the insertion film **18** are formed by, for example, sputtering, vacuum evaporation, or CVD. Then, the insertion film **18** is patterned into a desired shape by photolithography and etching. The insertion film **18** may be formed by liftoff.

As illustrated in FIG. **7**C, a second piezoelectric film **14***b* is formed on the first piezoelectric film **14***a* and the insertion film **18**. The second piezoelectric film **14***b* is formed by, for example, sputtering, vacuum evaporation, or CVD. The first and second piezoelectric films **14***a* and **14***b* form the piezoelectric film **14**. The lower and upper layers **16***a* and **16***b* are formed, as the upper electrode **16**, on the piezoelectric film **14**. The upper electrode **16** is formed by, for example, sputtering, vacuum evaporation, or CVD. Here, the lower layer **16***a* of the upper electrode **16** is formed so that the film thickness differs between the center region **20***a* and the outer peripheral region **20***b* of the resonance region **20**. The lower layer **16***a* may be formed as follows. The lower layer **16***a* with a film thickness equal to the film thickness in the outer peripheral region **20***b* in which the film thickness is relatively thin is formed across the entire surface, and then the lower layer **16***a* is additionally formed in the center region **20***a*. Alternatively, the lower layer **16***a* with a film thickness equal to the film thickness in the center region **20***a* in which the film thickness is relatively thick is formed across the entire surface, and then the lower layer **16***a* formed in the outer peripheral region **20***b* is etched. Then, the upper electrode **16** is patterned into a desired shape by photolithography and etching. The frequency adjusting film **24** is formed on the upper electrode **16** by, for example, sputtering or CVD.

In the parallel resonator P of FIG. **6**C, the lower layer **16***a* of the upper electrode **16** is formed, and the mass load film **26** is then formed by, for example, sputtering, vacuum evaporation method, or CVD. The mass load film **26** is patterned into a desired shape by photolithography and etching. The upper layer **16***b* of the upper electrode **16** is then formed.

After the formation of the frequency adjusting film **24**, an etching liquid to etch the sacrifice layer **32** is introduced into the sacrifice layer **32** below the lower electrode **12** through the hole portion **30** and the introduction path **28** (see FIG. **6**A). This process removes the sacrifice layer **32**. The substance used to etch the sacrifice layer **32** is preferably a substance that does not etch materials included in the resonator except the sacrifice layer **32**. For example, the etching substance is preferably a substance that does not etch the lower electrode **12** or the piezoelectric film **14** with which the etching substance contacts. The stress on the multilayered film including the lower electrode **12**, the piezoelectric film **14**, and the upper electrode **16** is configured to be a compression stress. This configuration allows the multilayered film to bulge out to the opposite side of the substrate **10** so as to separate from the substrate **10** when the sacrifice layer **32** is removed. Thus, the air gap **22** having a dome-shaped bulge is formed between the substrate **10** and the lower electrode **12**. The process including the above steps forms the piezoelectric thin film resonator **200** of the second embodiment.

A description will next be given of a simulation conducted on the piezoelectric thin film resonator **200** of the second embodiment by the inventors. The inventors investigated how the film thickness of the upper electrode **16** in the outer peripheral region **20***b* affects spurious occurring at frequencies less than the resonant frequency with respect to the piezoelectric thin film resonator **200** of the second embodiment illustrated in FIG. **6**A and FIG. **6**B by using a finite element method. The simulation was conducted on first and second specimens (the second embodiment), and a third specimen (a third comparative example).

The first specimen was configured so that the lower layer **12***a* of the lower electrode **12** was made of a Cr film with a thickness of 100 nm, the upper layer **12***b* was made of a Ru film with a thickness of 200 nm, and the piezoelectric film **14** was made of an AlN film with a thickness of 1260 nm. The upper electrode **16** was configured to include only the lower layer **16***a* made of a Ru film, and to have a thickness of 230 nm in the center region **20***a* and 50 nm in the outer peripheral region **20***b*. The insertion film **18** was configured to be made of a SiO_2 film with a thickness of 125 nm, and the length of the insertion film **18** inserted into the resonance region **20** (i.e., the width of the outer peripheral region **20***b*) was configured to be 2.5 μm.

The second specimen was configured to be the same as the first specimen except that the upper electrode **16** had a thickness of 60 nm in the outer peripheral region **20***b*. The third specimen was configured to be the same as the first specimen except that the upper electrode **16** had a thickness of 230 nm, which is equal to the thickness in the center region **20***a*, in the outer peripheral region **20***b*.

Table 1 presents the simulation results of the cutoff frequencies of the center regions **20***a* and the outer peripheral regions **20***b* of the resonance regions **20** of the first through third specimens. As presented in table 1, in the first specimen, the cutoff frequency in the center region **20***a* is equal to the cutoff frequency in the outer peripheral region **20***b*, while in the second specimen, the cutoff frequency in the center region **20***a* is close to the cutoff frequency in the outer peripheral region **20***b*. In the third specimen, the cutoff frequency in the center region **20***a* is away from the cutoff frequency in the outer peripheral region **20***b*.

TABLE 1

	Cutoff frequency in the center region [MHz]	Cutoff frequency in the outer peripheral region [MHz]
First specimen (second embodiment)	2010	2010
Second specimen (second embodiment)	2010	1978
Third specimen (third comparative example)	2010	1616

FIG. **8**A and FIG. **8**B illustrate the results of a simulation investigating spurious. FIG. **8**A illustrates a reflection characteristic (S**11**) near the resonant frequency, and FIG. **8**B is a Smith chart. The solid lines indicate the simulation result of the first specimen, the chain lines indicate the simulation result of the second specimen, and the dotted lines indicate the simulation result of the third specimen. As presented in table 1, FIG. **8**A, and FIG. **8**B, it is confirmed that the spurious occurring at frequencies less than the resonant frequency is reduced when the thickness of the upper electrode **16** is made thinner in the outer peripheral region **20***b* than in the center region **20***a* to make the cutoff frequencies in the center region **20***a* and the outer peripheral region **20***b* close to each other.

The inventors next investigated the dispersion curves of the thickness extension modes in the center region **20***a* and the outer peripheral region **20***b* with respect to the first specimen by using the finite element method. FIG. **9**A and FIG. **9**B illustrate the results of a simulation investigating the dispersion curves. FIG. **9**A illustrates the dispersion curve of the thickness extension mode in the center region **20***a*, and FIG. **9**B illustrates the dispersion curve of the thickness extension mode in the outer peripheral region **20***b*. As illustrated in FIG. **9**A and FIG. **9**B, the cutoff frequency at which the wave number is 0 (zero) is 2010 MHz in both cases, and the minimum frequency (the frequency at which the slope is zero) of the dispersion curve of the mode S1 is approximately 1905 MHz in FIG. **9**A, and approximately 1935 MHz in FIG. **9**B. This result allows to confirm that spurious occurring at frequencies less than the resonant frequency is reduced when the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the outer peripheral region **20***b* is made less than the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the center region **20***a*.

Therefore, the insertion film **18** is formed in the outer peripheral region **20***b*, and the film thickness of the upper electrode **16** is made less in the outer peripheral region **20***b* than in the center region **20***a* to make the cutoff frequency in the outer peripheral region **20***b* approximately equal to the cutoff frequency in the center region **20***a* to make the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the outer peripheral region **20***b* less than the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the center region **20***a*. The simulation assures that the above configuration reduces spurious.

The inventors next investigated the Q-value and the electromechanical coupling coefficient k2 at the antiresonant frequency with respect to the first specimen by using the finite element method. For comparison, the simulation was also conducted on a fourth specimen that was the piezoelectric thin film resonator **1100** of the second comparative example illustrated in FIG. **4**A. The fourth specimen was configured so that the upper electrode **66** had a thickness of 230 nm in the center region **68***a,* 220 nm in the first outer peripheral region **68***c*, and 330 nm in the second outer peripheral region **68***d*. Additionally, the first outer peripheral region **68***c* was configured to have a length of 4.0 μm, and the second outer peripheral region **68***d* was configured to have a length of 2.5 μm. Other configurations were the same as those of the first specimen. Table 2 presents the simulation results of the Q-value and the electromechanical coupling coefficient k2 at the antiresonant frequency. As presented in table 2, in the first specimen, the Q-value and the electromechanical coupling coefficient k2 at the antiresonant frequency are improved compared with those in the fourth specimen.

TABLE 2

	Q-value at the antiresonant frequency	Electromechanical coupling coefficient k2 [%]
First specimen (second embodiment)	1467	7.18
Fourth specimen (second comparative example)	1354	7.08

Accordingly, the insertion film **18** is formed in the outer peripheral region **20***b*, and the film thickness of the upper electrode **16** is made less in the outer peripheral region **20***b* than in the center region **20***a* to make the cutoff frequency in the outer peripheral region **20***b* approximately equal to the cutoff frequency in the center region **20***a* to make the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the outer peripheral region **20***b* less than the difference between the cutoff frequency and the minimum frequency of the dispersion curve of the thickness extension mode in the center region **20***a*. The simulation assures that the above configuration improves the Q-value and the electromechanical coupling coefficient k**2** at the antiresonant frequency.

The inventors next investigated the dispersion curves of the thickness extension modes in the outer peripheral regions **20***b* of piezoelectric thin film resonators using different materials for the insertion film **18** by using the finite element method. The piezoelectric thin film resonators used for the simulation were configured to be the same as the first specimen except the insertion film **18**. The insertion film **18** was configured to have a thickness of 125 nm and a length of 1.9 μm. Table 3 lists the materials of the insertion film **18** used for the simulation and the material constant of each material. In table 3, the acoustic impedance is represented by a value obtained by normalizing the product of the density and the Young's modulus by the acoustic impedance of AlN. As listed in table 3, the simulation was conducted by using SiO_2, Ru, Cr, Ti, Al, Ta, W, or Mo for the insertion film **18**.

TABLE 3

Insertion film	Density [g/cm^3]	Poisson's ratio	Young's modulus [GPa]	Acoustic impedance
SiO_2	2.2	0.175	79	0.17
Ru	12.37	0.3	447	5.47
Cr	7.14	0.21	279	1.97
Ti	4.507	0.32	116	0.52
Al	2.7	0.35	70	0.19
Ta	16.65	0.34	186	3.06
W	19.25	0.28	411	7.83
Mo	10.28	0.28	329	3.35
AlN	3.26	0.25	310	1

FIG. **10** illustrates the results of a simulation investigating the dispersion curves of the thickness extension modes in the outer peripheral regions **20***b* within the resonance regions **20** of the piezoelectric thin film resonators using different materials for the insertion film **18**. The bold dashed line indicates the dispersion curve of the thickness extension mode in the center region **20***a* of the resonance region **20**. As illustrated in FIG. **10**, when the insertion film **18** is made of SiO_2 or Al, the minimum frequency of the dispersion curve of the thickness extension mode in the outer peripheral region **20***b* shifts to a frequency greater than the minimum frequency of the dispersion curve of the thickness extension mode in the center region **20***a*.

The inventors next investigated the reflection characteristic (S**11**) around the resonant frequencies of the piezoelectric thin film resonators using different materials for the insertion film **18** by using the finite element method. For comparison, the reflection characteristic (S**11**) around the resonant frequency of the piezoelectric thin film resonator without the insertion film **18** was also investigated. FIG. **11**A and FIG. **11**B are cross-sectional views of the piezoelectric thin film resonators used for the simulation. As illustrated in FIG. **11**A, the lower layer **12***a* of the lower electrode **12** on the substrate **10** made of Si was configured to be made of a Cr film with a thickness of 100 nm, and the upper layer **12***b* was configured to be made of a Ru film with a thickness of 200 nm. The piezoelectric film **14** was configured to be made of an AlN film with a thickness of 1260 nm. The upper electrode **16** was configured to be made of only a Ru film, to have a thickness of 230 nm in the center region **20***a*, and to have a thickness, in the outer peripheral region **20***b*, that allows the cutoff frequency in the outer peripheral region **20***b* to be equal to the cutoff frequency in the center region **20***a*. The insertion film **18** was configured to have a thickness of 125 nm and a length of 1.9 μm. As illustrated in FIG. **11**B, in the piezoelectric thin film resonator without the insertion film **18**, the upper electrode **16** was configured to be made of only a Ru film, and to have a uniform thickness of 230 nm. Other configurations are the same as those illustrated in FIG. **11**A.

FIG. **12**A illustrates the simulation result of the reflection characteristic (S**11**) around the resonant frequency of the piezoelectric thin film resonator without the insertion film **18**. FIG. **12**B through FIG. **13**C illustrate the simulation results of the reflection characteristics (S**11**) around the resonant frequencies of the piezoelectric thin film resonators using different materials for the insertion film **18**. FIG. **12**A through FIG. **13**C reveals that spurious at frequencies less than the resonant frequency is reduced when the insertion film **18** is made of a SiO_2 film, a Ti film, or an Al film. Especially when the insertion film **18** is made of a SiO_2 film, spurious at frequencies less than the resonant frequency is substantially reduced.

Therefore, to reduce spurious, the insertion film **18** is preferably a film, such as Ti or Al, with an acoustic impedance less than that of AlN, more preferably a film, such as SiO_2, with an acoustic impedance less than that of AlN and a Poisson's ratio less than that of AlN. The insertion film **18** may be a silicon oxide film containing another element. The examples of another element include, but not limited to, for example, fluorine and boron. The silicon oxide film containing such an element has an acoustic impedance less than that of AlN and a Poisson's ratio less than that of AlN.

In the second embodiment, as illustrated in FIG. **6**A through FIG. **6**C, the insertion film **18** is formed in the entire periphery of the outer peripheral region **20***b*, and the upper electrode **16** in the entire periphery of the outer peripheral region **20***b* is thinner than the upper electrode **16** in the center region **20***a*. This configuration effectively reduces spurious.

FIG. **14**A is a top view of a piezoelectric thin film resonator **210** of a first variation of the second embodiment, and FIG. **14**B is a cross-sectional view taken along line A-A of FIG. **14**A. FIG. **14**B is a cross-sectional view of the series resonator S of the ladder-type filter. As in FIG. **6**C, the parallel resonator P has a structure in which the mass load film **26** is located between the layers of the upper electrode **16** in FIG. **14**A, and thus the description will be omitted (the same applies to a second variation of the second embodiment through a fifth embodiment).

As illustrated in FIG. **14**A and FIG. **14**B, in the piezoelectric thin film resonator **210** of the first variation of the second embodiment, the upper electrode **16** is thinner not only in the outer peripheral region **20***b* within the resonance region **20**, but also from the outer peripheral region **20***b* to the outside of the resonance region **20**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

FIG. **15**A is a top view of a piezoelectric thin film resonator **220** in accordance with the second variation of the second embodiment, and FIG. **15**B is a cross-sectional view taken along line A-A of FIG. **15**A. As illustrated in FIG. **15**A and FIG. **15**B, in the piezoelectric thin film resonator **220** of the second variation of the second embodiment, the insertion film **18** is formed on the upper surface of the piezoelectric film **14**. In other words, the insertion film **18** is formed between the piezoelectric film **14** and the upper electrode **16**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

FIG. **16**A is a top view of a piezoelectric thin film resonator **230** in accordance with the third variation of the second embodiment, and FIG. **16**B is a cross-sectional view taken along line A-A of FIG. **16**A. As illustrated in FIG. **16**A and FIG. **16**B, in the piezoelectric thin film resonator **230** of the third variation of the second embodiment, the insertion film **18** is formed on the lower surface of the piezoelectric film **14**. In other words, the insertion film **18** is formed between the piezoelectric film **14** and the lower electrode **12**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

As in the second embodiment and the second and third variations of the second embodiment, the insertion film **18** may be formed in the piezoelectric film **14**, or may be formed on the upper surface or the lower surface of the piezoelectric film **14**. Alternatively, the insertion film **18** may be formed in the piezoelectric film **14**, on the upper surface of the piezoelectric film **14**, and on the lower surface of the piezoelectric film **14**.

FIG. **17**A is a top view of a piezoelectric thin film resonator **240** in accordance with the fourth variation of the second embodiment, and FIG. **17**B is a cross-sectional view taken along line A-A of FIG. **17**A. As illustrated in FIG. **17**A and FIG. **17**B, in the piezoelectric thin film resonator **240** of the fourth variation of the second embodiment, the insertion film **18** is formed in only a part of the outer peripheral region **20***b* within the resonance region **20**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

FIG. **18**A is a top view of a piezoelectric thin film resonator **250** in accordance with the fifth variation of the second embodiment, and FIG. **18**B is a cross-sectional view taken along line A-A of FIG. **18**A. As illustrated in FIG. **18**A and FIG. **18**B, in the piezoelectric thin film resonator **250** of the fifth variation of the second embodiment, the upper electrode **16** is made thinner in only a part of the outer peripheral region **20***b* within the resonance region **20**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

The second embodiment through the fifth variation of the second embodiment have described a case where the lower layer **16***a* of the upper electrode **16** is thinner in the outer peripheral region **20***b* than in the center region **20***a* as an example, but the upper layer **16***b* of the upper electrode **16** may be thinner in the outer peripheral region **20***b*, or both the lower and upper layers **16***a* and **16***b* may be thinner. The structure of the upper electrode **16** is not limited to the two-layer structure of the lower and upper layers **16***a* and **16***b*, and may be a single-layer structure or a layer structure including three or more layers. The lower electrode **12** may also have a single-layer structure or a layer structure including three or more layers.

Third Embodiment

FIG. **19**A is a top view of a piezoelectric thin film resonator **300** in accordance with the third embodiment, and FIG. **19**B is a cross-sectional view taken along line A-A of FIG. **19**A. As illustrated in FIG. **19**A and FIG. **19**B, in the piezoelectric thin film resonator **300** of the third embodiment, the lower layer **16***a* of the upper electrode **16** is not formed and only the upper layer **16***b* is formed in the outer peripheral region **20***b* of the resonance region **20**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

As in the third embodiment, the number of metal layers of the upper electrode **16** in the outer peripheral region **20***b* within the resonance region **20** may be made less than the number of metal layers of the upper electrode **16** in the center region **20***a* to make the upper electrode **16** in the outer peripheral region **20***b* thinner than the upper electrode **16** in the center region **20***a*.

Fourth Embodiment

FIG. **20**A is a top view of a piezoelectric thin film resonator **400** in accordance with the fourth embodiment, and FIG. **20**B is a cross-sectional view taken along line A-A of FIG. **20**A. As illustrated in FIG. **20**A and FIG. **20**B, in the piezoelectric thin film resonator **400** of the fourth embodiment, the piezoelectric film **14** in the outer peripheral region **20***b* within the resonance region **20** is thinner than the piezoelectric film **14** in the center region **20***a*. The upper electrode **16** has an identical thickness in the center region **20***a* and the outer peripheral region **20***b*. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

Fifth Embodiment

FIG. **21**A is a top view of a piezoelectric thin film resonator **500** in accordance with the fifth embodiment, and FIG. **21**B is a cross-sectional view taken along line A-A of FIG. **21**A. As illustrated in FIG. **21**A and FIG. **21**B, in the piezoelectric thin film resonator **500** of the fifth embodiment, the lower electrode **12** in the outer peripheral region **20***b* within the resonance region **20** is thinner than the lower electrode **12** in the center region **20***a*. The upper electrode **16** has an identical thickness in the center region **20***a* and the outer peripheral region **20***b*. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

As in the second through fifth embodiments, at least one of the lower electrode **12**, the piezoelectric film **14**, and the upper electrode **16** is only required to be thinner in the outer peripheral region **20***b* within the resonance region **20** than in the center region **20***a*. Two or more of the lower electrode **12**, the piezoelectric film **14**, and the upper electrode **16** may be thinner in the outer peripheral region **20***b* than in the center region **20***a*.

As in the first variation of the second embodiment, the lower electrode **12** may be thinner not only in the outer peripheral region **20***b* within the resonance region **20** but also from the outer peripheral region **20***b* to the outside of the resonance region **20** in the fifth embodiment. As in the fifth variation of the second embodiment, the lower electrode **12** may be thinner in only a part of the outer peripheral region **20***b*.

As in the third embodiment, the number of metal layers of the lower electrode **12** in the outer peripheral region **20***b* within the resonance region **20** may be made less than the number of metal layers of the lower electrode **12** in the center region **20***a* to make the lower electrode **12** in the outer peripheral region **20***b* thinner than the lower electrode **12** in the center region **20***a* in the fifth embodiment. That is, at least one of the upper and lower electrodes **16** and **12** in the outer peripheral region **20***b* may have the number of metal layers less than the number of metal layers of the at least one of the upper and lower electrodes **16** and **12** in the center region **20***a*.

The fifth embodiment has described a case where the lower layer **12***a* of the lower electrode **12** is thinner in the outer peripheral region **20***b* than in the center region **20***a*, but the upper layer **12***b* of the lower electrode **12** may be thinner in the outer peripheral region **20***b*, or both the lower and upper layers **12***a* and **12***b* may be thinner.

As in the second and third variations of the second embodiment, the insertion film **18** may be formed on the upper surface or the lower surface of the piezoelectric film **14** in the third through fifth embodiments.

Sixth Embodiment

FIG. **22** is a cross-sectional view of a piezoelectric thin film resonator **600** in accordance with a sixth embodiment. As illustrated in FIG. **22**, the piezoelectric thin film resonator **600** of the sixth embodiment includes a recessed portion formed in the principal surface of the substrate **10**. The lower electrode **12** is formed approximately flat on the principal surface of the substrate **10**. This allows the recessed portion of the substrate **10** to function as an air gap **22***a*. The air gap **22***a* is formed so as to include the resonance region **20**. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted. The air gap **22***a* may be formed so as to penetrate through the substrate **10**.

The sixth embodiment has described a case where the air gap **22***a* is formed instead of the air gap **22** of the second embodiment, but the air gap **22***a* may be formed instead of the air gap **22** in the first variation of the second embodiment through the fifth embodiment.

Seventh Embodiment

FIG. **23** is a cross-sectional view of a piezoelectric thin film resonator **700** in accordance with a seventh embodiment. As illustrated in FIG. **23**, the piezoelectric thin film resonator **700** of the seventh embodiment includes an acoustic mirror **40** formed below the lower electrode **12** of the resonance region **20**. The acoustic mirror **40** is a film reflecting the acoustic wave propagating through the piezoelectric film **14**, and includes a film **42** with a low acoustic impedance and a film **44** with a high acoustic impedance alternately formed. The film **42** with a low acoustic impedance and the film **44** with a high acoustic impedance basically have a film thickness of λ/4 (λ is the wavelength of the acoustic wave), but the film thickness may be appropriately changed to obtain desired characteristics. In addition, the number of stacking layers of the film **42** with a low acoustic impedance and the film **44** with a high acoustic impedance is freely selected. Other configurations are the same as those of the piezoelectric thin film resonator **200** of the second embodiment, and thus the description is omitted.

The seventh embodiment has described a case where the acoustic mirror **40** is formed instead of the air gap **22** of the second embodiment, but the acoustic mirror **40** may be also formed instead of the air gap **22** in the first variation of the second embodiment through the fifth embodiment.

As described above, the piezoelectric thin film resonator may be a Film Bulk Acoustic Resonator (FBAR) in which the air gap **22** or **22***a* is formed between the lower electrode **12** and the substrate **10** in the resonance region **20** as in the first through sixth embodiments. As in the seventh embodiment, the piezoelectric thin film resonator may be a Solidly Mounted Resonator (SMR) in which the acoustic mirror **40** is formed below the lower electrode **12** in the resonance region **20**.

The second through seventh embodiments have described a case where the resonance region **20** has an elliptical shape as an example, but the resonance region **20** may have another shape including a polygonal shape such as a quadrangle shape or a pentagonal shape.

Eighth Embodiment

FIG. **24** illustrates a filter **800** in accordance with an eighth embodiment. As illustrated in FIG. **24**, the filter **800** of the eighth embodiment is a ladder-type filter that includes one or more series resonators S**1** through S**4** connected in series and one or more parallel resonators P**1** through P**4** connected in parallel between input and output terminals T**1** and T**2**. At least one of the series resonators S**1** through S**4** and the parallel resonators P**1** through P**4** may be the piezoelectric thin film resonator according to any one of the first through seventh embodiments.

Ninth Embodiment

FIG. **25** illustrates a duplexer **900** in accordance with a ninth embodiment. As illustrated in FIG. **25**, the duplexer **900** of the ninth embodiment includes a transmit filter **50** connected between an antenna terminal Ant and a transmit terminal Tx and a receive filter **52** connected between the antenna terminal Ant and a receive terminal Rx. The transmit filter **50** and the receive filter **52** have different passbands. The transmit filter **50** passes signals within the transmit band, among signals input from the transmit terminal Tx, to the antenna terminal Ant as a transmission signal, and suppresses signals in other bands. The receive filter **52** passes signals within the receive band, among signals input from the antenna terminal Ant, to the receive terminal Rx as a reception signal, and suppresses other bands. At least one of the transmit filter **50** and the receive filter **52** may be the filter of the eighth embodiment.

Although the embodiments of the present invention have been described in detail, it is to be understood that the various change, substitutions, and alterations could be made hereto without departing from the spirit and scope of the invention.

What is claimed is:

1. A piezoelectric thin film resonator comprising:

a substrate;

a piezoelectric film that is located on the substrate and has a Poisson's ratio of 0.33 or less;

a lower electrode and an upper electrode that face each other across the piezoelectric film; and

an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region,

wherein at least one of the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region, and

wherein a cutoff frequency in the outer peripheral region within the resonance region is approximately equal to a cutoff frequency in the center region of the resonance region.

2. The piezoelectric thin film resonator according to claim **1**, wherein

an air gap is formed between the substrate and the lower electrode in the resonance region.

3. The piezoelectric thin film resonator according to claim **1**, wherein

a difference between a cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the outer peripheral region within the resonance region is less than a difference between a cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the center region of the resonance region.

4. The piezoelectric thin film resonator according to claim **1**, wherein

a multilayered film including the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than a multilayered film including the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region.

5. The piezoelectric thin film resonator according to claim **1**, wherein

the insertion film has an acoustic impedance less than an acoustic impedance of the piezoelectric film.

6. The piezoelectric thin film resonator according to claim **1**, wherein

the insertion film has a Poisson's ratio less than a Poisson's ratio of the piezoelectric film.

7. The piezoelectric thin film resonator according to claim **1**, wherein

the insertion film is a silicon oxide film or a silicon oxide film containing another element.

8. The piezoelectric thin film resonator according to claim **1**, wherein

the piezoelectric film is an aluminum nitride film or an aluminum nitride film containing another element.

9. A filter comprising the piezoelectric thin film resonator according to claim **1**.

10. A piezoelectric thin film resonator comprising:

a substrate;

a piezoelectric film that is located on the substrate and has a Poisson's ratio of 0.33 or less;

a lower electrode and an upper electrode that face each other across the piezoelectric film; and

an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region,

wherein a cutoff frequency in the outer peripheral region within the resonance region is approximately equal to a cutoff frequency in the center region of the resonance region, and

a difference between the cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the outer peripheral region within the resonance region is less than a difference between the cutoff frequency and a minimum frequency of a dispersion curve of a thickness extension mode in the center region of the resonance region.

11. The piezoelectric thin film resonator according to claim **10**, wherein

the insertion film has an acoustic impedance less than an acoustic impedance of the piezoelectric film.

12. The piezoelectric thin film resonator according to claim **10**, wherein

the insertion film is a silicon oxide film or a silicon oxide film containing another element.

13. The piezoelectric thin film resonator according to claim **10**, wherein

the insertion film has a Poisson's ratio less than a Poisson's ratio of the piezoelectric film.

14. The piezoelectric thin film resonator according to claim **10**, wherein

the piezoelectric film is an aluminum nitride film or an aluminum nitride film containing another element.

15. A filter comprising the piezoelectric thin film resonator according to claim **10**.

16. The piezoelectric thin film resonator according to claim **10**, wherein

an air gap is formed between the substrate and the lower electrode in the resonance region.

17. A piezoelectric thin film resonator comprising:

a substrate;

a piezoelectric film that is located on the substrate and has a Poisson's ratio of 0.33 or less;

a lower electrode and an upper electrode that face each other across the piezoelectric film; and

an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region,

wherein at least one of the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region, and

wherein at least one of the lower electrode and the upper electrode in the outer peripheral region within the resonance region has a smaller number of metal layers than the at least one of the lower electrode and the upper electrode in the center region of the resonance region.

18. A piezoelectric thin film resonator comprising:

a substrate;

a piezoelectric film that is located on the substrate and is an aluminum nitride film or an aluminum nitride film containing another element;

a lower electrode and an upper electrode that face each other across the piezoelectric film; and

an insertion film that is located in the piezoelectric film or on a lower surface or an upper surface of the piezoelectric film in an outer peripheral region within a resonance region, in which the lower electrode and the upper electrode face each other across the piezoelectric film, and is not located in a center region of the resonance region,

wherein at least one of the lower electrode, the piezoelectric film, and the upper electrode in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region, and

wherein a laminated film included the lower electrode, the piezoelectric film, the upper electrode, and the insertion film in the outer peripheral region within the resonance region is thinner than a laminated film included the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region.

19. The piezoelectric thin film resonator according to claim **18**, wherein,

at least one of the lower electrode, the piezoelectric film, and the upper electrode in a region where the insertion film is provided in the outer peripheral region within the resonance region is thinner than the at least one of the lower electrode, the piezoelectric film, and the upper electrode in the center region of the resonance region.

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