DESCRIPTION

Title of Invention: PIEZOELECTRIC RESONATOR AND METHOD FOR MANUFACTURING THE SAME

Technical Field

[0001]

The present invention relates to a piezoelectric resonator and a method for manufacturing the same.

Background Art

[0002]

Heretofore, there has been known a piezoelectric MEMS (Micro Electro Mechanical Systems) vibrator in which an excitation portion including a piezoelectric thin film is formed on a single crystal Si.

[0003]

For example, in the following Patent Document 1, a piezoelectric MEMS vibrator in which a piezoelectric thin film formed of scandium-containing aluminum nitride is provided on a Si single crystal has been disclosed. The piezoelectric MEMS vibrator described above has a so-called Cavity SOI (Silicon on insulator) structure in which a cavity portion is provided in a Si single crystal.

[0004]

In addition, in the following Patent Document 2 and Non-Patent Documents 1 and 2, a piezoelectric MEMS vibrator in which a piezoelectric film layer formed of aluminum

nitride is provided on a SOI substrate has also been disclosed.

Citation List

Patent Document

[0005]

Patent Document 1: Japanese Unexamined Patent Application Publication No. 2009-10926

Patent Document 2: U.S. Patent Application Publication No. 2010/0013360A1

Non-Patent Document

[0006]

Non-Patent Document 1: Procedia Chemistry1 (2009) 1395 to 1398

Non-Patent Document 2: Frequency Control Symposium, 2007, IEEE International 1210 to 1213

Summary of Invention

Technical Problem

[0007]

However, according to the piezoelectric MEMS vibrators disclosed in Patent Documents 1 and 2 and Non-Patent Documents 1 and 2, the variation in thickness of the Si layer was large. On the other hand, the resonance frequency depends on the thickness of the Si layer. Hence, according to the piezoelectric resonators disclosed in Patent Documents 1 and 2 and Non-Patent Documents 1 and 2, the

variation in frequency was liable to occur. Hence, the frequency was required to be controlled by a trimming step provided therefor.

[0008]

An object of the present invention is to provide a piezoelectric resonator capable of suppressing the variation in resonance frequency caused by the variation in thickness of Si and a method for manufacturing the piezoelectric resonator described above.

Solution to Problem

[0009]

A piezoelectric resonator according to the present invention comprises a single crystal Si, a piezoelectric thin film formed from aluminum nitride and provided on the single crystal Si, and a first and a second electrode provided so as to sandwich the piezoelectric thin film. The piezoelectric thin film formed from aluminum nitride is doped with an element excluding nitrogen and aluminum. A synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si substantially coincides with the acoustic velocity thereof.

[0010]

In a specific aspect of the piezoelectric resonator according to the present invention, the doping described above is performed so that the synthetic acoustic velocity

of the acoustic velocities of the portions other than the single crystal Si is made to substantially coincide with the acoustic velocity thereof.

[0011]

In another specific aspect of the piezoelectric resonator according to the present invention, the doping described above is performed using at least one type of element selected from the group consisting of scandium, yttrium, lutetium, and dysprosium.

[0012]

In still another specific aspect of the piezoelectric resonator according to the present invention, the single crystal Si is doped with an n-type dopant, and the concentration of the n-type dopant is $1\times10^{19}/cm^3$ or more.

[0013]

The piezoelectric resonator according to the present invention preferably further comprises a silicon oxide film layer disposed so as to be in contact with the first electrode or the second electrode.

[0014]

The piezoelectric resonator according to the present invention preferably further comprises a dielectric film which has a high acoustic velocity as compared to that of the piezoelectric thin film formed from aluminum nitride doped with an element excluding nitrogen and aluminum and

which is disposed so as to be in contact with the first electrode or the second electrode. The dielectric film having a high acoustic velocity described above is preferably formed from aluminum nitride doped with at least one element of boron and carbon.

[0015]

In the piezoelectric resonator according to the present invention, the vibration mode is preferably width spreading vibration or in-plane bending vibration.

[0016]

A method for manufacturing the piezoelectric resonator according to the present invention comprises the steps of preparing the single crystal Si, forming the first electrode on the single crystal Si, forming the piezoelectric thin film from aluminum nitride on the first electrode, and forming the second electrode on the piezoelectric thin film. The step of forming the piezoelectric thin film includes a step of doping an element excluding nitrogen and aluminum into the aluminum nitride in advance so that the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si is made to substantially coincide with the acoustic velocity thereof.

Advantageous Effects of Invention

[0017]

In the piezoelectric resonator according to the present

invention, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si substantially coincides with the acoustic velocity thereof. As a result, the resonant frequency is no longer dependent on the thickness. Hence, the variation in resonant frequency caused by the variation in thickness can be suppressed.

[0018]

By the method for manufacturing the piezoelectric resonator according to the present invention, a piezoelectric resonator capable of suppressing the variation in resonance frequency caused by the variation in thickness of Si can be provided.

Brief Description of Drawings

[0019]

[Fig. 1] Fig. 1 is a perspective view showing the appearance of a piezoelectric resonator according to a first embodiment of the present invention.

[Fig. 2] Fig. 2 is a cross-sectional view of the portion along the line A-A shown in Fig. 1.

[Fig. 3] Fig. 3 is a graph showing the relationship of the acoustic velocity and a Sc concentration with respect to aluminum nitride (AlN).

[Fig. 4] Fig. 4 is a graph showing the relationship of the acoustic velocity and a dopant concentration of each of

Sc, Y, Dy, and Lu with respect to aluminum nitride (AlN).

[Fig. 5] Fig. 5 is a cross-sectional view illustrating a first modified example of the first embodiment.

[Fig. 6] Fig. 6 is a graph showing the relationship of a synthetic acoustic velocity (synthetic acoustic velocity of the acoustic velocity of ScAlN and the acoustic velocity of SiO_2) and a ScAlN film thickness ratio (ScAlN/ScAlN+SiO_2) obtained when ScAlN having a Sc concentration of 15 atomic percent is used.

[Fig. 7] Fig. 7 is a graph showing the relationship of the piezoelectric constant (d_{33}) and the scandium (Sc) concentration.

[Fig. 8] Fig. 8 is a cross-sectional view illustrating a second modified example of the first embodiment.

[Fig. 9] Fig. 9 is a cross-sectional view illustrating a third modified example of the first embodiment.

[Fig. 10] Fig. 10 is a graph showing the relationship of the acoustic velocity and a dopant concentration of each of B and C with respect to aluminum nitride.

[Fig. 11] Fig. 11 is a perspective view showing the appearance of a piezoelectric resonator according to a second embodiment of the present invention.

[Fig. 12] Fig. 12 is a cross-sectional view of the portion along the line B-B shown in Fig. 11.

[Fig. 13] Fig. 13 is a graph showing the relationship

of the variation in frequency and the thickness of Si of a width spreading vibrator according to Example 1.

[Fig. 14] Fig. 14 is a graph showing the relationship of the variation in frequency and the thickness of Si of an in-plane bending vibrator according to Example 2.

[Fig. 15] Fig. 15 is a graph showing the relationship of the variation in frequency and the thickness of Si of a width spreading vibrator according to Example 3.

[Fig. 16] Fig. 16 is a graph showing the relationship of the variation in frequency and the thickness of Si of a width spreading vibrator according to Example 4.

[Fig. 17] Fig. 17 is a cross-sectional view illustrating a modified example of the second embodiment.

Description of Embodiments

[0020]

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

[0021]

Fig. 1 is a perspective view showing the appearance of a piezoelectric resonator 1 according to a first embodiment of the present invention. The piezoelectric resonator 1 is a resonator which includes support portions 2a and 2b, a vibration plate 3, and connection portions 4a and 4b and which uses width spreading vibration.

[0022]

The vibration plate 3 is a rectangular-shaped plate and has a length direction and a width direction. The vibration plate 3 is connected to the support portions 2a and 2b with the connection portions 4a and 4b, respectively, provided therebetween. That is, the vibration plate 3 is supported by the support portions 2a and 2b. The vibration plate 3 is a vibrating body which vibrates in a width direction in a width spreading vibration mode when an alternating electric field is applied.

[0023]

One end of each of the connection portions 4a and 4b is connected to a side-surface center of the vibration plate 3 at a short side. The side-surface center of the vibration plate 3 at a short side functions as the node of the width spreading vibration.

[0024]

The support portions 2a and 2b are connected to the other ends of the connection portions 4a and 4b, respectively. The support portions 2a and 2b each extend to the two sides of each of the connection portions 4a and 4b. Although not particularly limited, in this embodiment, the length of each of the support portions 2a and 2b is the same as that of the short side of the vibration plate 3.

[0025]

The support portions 2a and 2b and the connection

portions 4a and 4b each may be formed of the same material as that of the vibration plate 3 or may be formed of a different material therefrom.

[0026]

Fig. 2 is a cross-sectional view of the portion along the line A-A shown in Fig. 1. As shown in Fig. 2, the vibration plate 3 is formed of a single crystal Si 5, first and second electrodes 6 and 7, a piezoelectric thin film 8.

[0027]

In more particular, on the single crystal Si 5, the piezoelectric thin film 8 is provided. The first and the second electrodes 6 and 7 are provided so as to sandwich the piezoelectric thin film 8. In addition, in this embodiment, although not shown in the drawing, a seed layer may be provided on an upper surface 5a of the single crystal Si 5, and/or a protective layer may be provided on the upper surface of the second electrode 7. In addition, both the seed layer and the protective layer may not be provided. As the seed layer and the protective layer, the same material as that of the piezoelectric thin film 8 may be used.

[0028]

Although not particularly limited, the single crystal Si is preferably an n-type semiconductor which is a degenerate semiconductor and preferably has an n-type dopant concentration of $1\times10^{19}/cm^3$ or more. The reason for this is

that when a heavily doped n-type semiconductor is used, the variation in resonance frequency with the temperature can be further improved. In addition, as the n-type dopant described above, a group XV element, such as P, As, or Sb, may be mentioned by way of example.

[0029]

A material of each of the first and the second electrodes 6 and 7 is not particularly limited, and an appropriate metal, such as Mo, Ru, Pt, Ti, Cr, Al, Cu, Ag, or W, or an alloy thereof may be used. In order to improve the Q value of the resonator, a material having a high Q value is also effectively used as an electrode material, and hence, Mo or W is preferably used.

[0030]

The piezoelectric thin film 8 is formed of aluminum nitride doped with an element excluding nitrogen and aluminum. As the element which is to be doped, at least one type of element selected from the group consisting of scandium (Sc), yttrium (Y), lutetium (Lu), and dysprosium (Dy) is preferable. Sc which has a small rate of change in acoustic velocity with respect to the addition concentration and which is relatively strong against the variation in concentration is preferably used.

[0031]

In the piezoelectric resonator 1 of this embodiment, a

synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 substantially coincides with the acoustic velocity thereof. In addition, the acoustic velocity described in this specification represents a longitudinal wave acoustic velocity. In addition, although the acoustic velocities preferably exactly coincide with each other, they may substantially coincide with each other.

[0032]

The synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 is, for example, in this embodiment, the synthetic acoustic velocity of the acoustic velocities of the first and the second electrodes 6 and 7 and the acoustic velocity of the piezoelectric thin film 8. In general, compared to the thicknesses of the other layers, the thickness of each of the first and the second electrodes 6 and 7 is small, such as 1/20 to 1/4 of the thickness of the piezoelectric thin film 8, and has a small contribution to the acoustic velocity. Hence, in this specification, the acoustic velocities of the first and the second electrodes 6 and 7 are ignored.

[0033]

In this case, the synthetic acoustic velocity of the piezoelectric resonator 1 other than the single crystal Si 5

is the acoustic velocity of the piezoelectric thin film 8. Accordingly, in this embodiment, the acoustic velocity of the piezoelectric thin film 8 is required to coincide with the acoustic velocity of the single crystal Si 5.

[0034]

As a method which enables the acoustic velocity of the piezoelectric thin film 8 to coincide with the acoustic velocity of the single crystal Si 5, there may be mentioned a method in which with respect to aluminum nitride forming the piezoelectric thin film 8, the dopant concentration of an element excluding nitrogen and aluminum is adjusted. In more particular, hereinafter, the above method will be described with reference to Fig. 3.

[0035]

Fig. 3 is a graph showing the relationship of the acoustic velocity and the Sc dopant concentration with respect to aluminum nitride (AlN). From Fig. 3, it is found that the acoustic velocity of a Sc-containing aluminum nitride (ScAlN) shown by a solid line in the graph is decreased with an increase in Sc concentration. The reason for this is that by addition of Sc, since Al is substituted with Sc, and the lattice distance in the a-axis direction is increased, Sc and Al atoms are likely to move in the c-axis direction, and Young's modulus is rapidly decreased. On the other hand, the acoustic velocity of the single crystal Si 5

shown by a dotted line is constant regardless of the Sc concentration. Hence, when the dopant concentration of Sc with respect to aluminum nitride is increased, at an X point in the graph, the acoustic velocity of ScAlN coincides with the acoustic velocity of the single crystal Si 5. As described above, when the dopant concentration of Sc is adjusted, the acoustic velocity of ScAlN (acoustic velocity of the piezoelectric thin film 8) can be made to coincide with the acoustic velocity of the single crystal Si 5.

[0036]

The resonance frequency (fr) of the piezoelectric resonator 1 of this embodiment is represented by the following equation (1).

[0037]

[Eq. 1]

$$fr = \frac{1}{2w}\sqrt{\frac{1}{\rho\, s_{33}^{E}}} = \frac{1}{2w} v_{total} \qquad \text{Equation (1)}$$

(fr: resonance frequency, w: widht, ρ: density, S^E: elastic compliance, ν_{total}: acoustic velocity of piezoelectric resonator)

[0038]

From Equation (1), it is found ν_{total} represented by the following equation (2) is only dependent on the thickness.

[0039]

[Eq. 2]

$$v_{total} = \frac{t_1 v_1 + t_2 v_2}{t_{total}}$$

Equation (3)

(ν_{total}: acoustic velocity of piezoelectric resonator, t_{total}: thickness of piezoelectric resonator, ν_1: acoustic velocity of single crystal Si, t_1: thickness of single crystal Si, ν_2: acoustic velocity of piezoelectric thin film, t_2: thickness of piezoelectric thin film)

[0040]

In the present invention, since the acoustic velocity of the piezoelectric thin film 8 is made to coincide with the acoustic velocity of the single crystal Si 5 by adjusting the dopant concentration of Sc, $\nu_1=\nu_2$ holds. In this case, ν_{total} is represented by $\nu_{total}=\nu_1$ as shown by the following equation (3).

[0041]

[Eq. 3]

$$v_{total} = \frac{t_1 v_1 + t_2 v_2}{t_{total}} = \frac{t_1 v_1 + t_2 v_1}{t_{total}} = v_1$$

Equation (3)

(ν_{total}: acoustic velocity of piezoelectric resonator, t_{total}: thickness of piezoelectric resonator, ν_1: acoustic velocity of single crystal Si, t_1: thickness of single crystal Si, ν_2: acoustic velocity of piezoelectric thin film, t_2: thickness of piezoelectric thin film)

[0042]

As shown by Equation (3), since v_{total} is not dependent on the thickness, the resonace frequency (fr) of Equaion (1) is also not dependent on the thickness. Hence, the variation in resonance frequency caused by the variaion in thickenss can be suppressed.

[0043]

Fig. 4 is a graph showing the relationship of the acoustic velocity and the dopant concentration of each of Sc, Y, Dy, and Lu with respect to aluminum nitride (AlN). From Fig. 4, it is found that even when Y, Dy, or Lu is used instead of Sc, as the dopant concentration is increased, the acoustic velocity can also be decreased so as to coincide with the acoustic velocity of the single crystal Si 5.

[0044]

Fig. 5 is a cross-sectional view illustrating a first modified example of the first embodiment. In this modified example, on the upper surface of the single crystal Si 5, a silicon oxide film 9 is further disposed. In addition, in this modified example, the acoustic velocities of the first and the second electrodes 6 and 7 are also ignored. Hence, in this modified example, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 is the synthetic acoustic velocity of the acoustic velocity of the piezoelectric thin film 8 and

the acoustic velocity of the silicon oxide film 9. In this case, the acoustic velocity of the silicon oxide film 9 is lower than the acoustic velocity of the single crystal Si 5. Hence, by changing the film thickness ratio (thickness of the piezoelectric thin film 8/total thickness of the piezoelectric thin film 8 and the silicon oxide film 9), the synthetic acoustic velocity described above can be made to coincide with the acoustic velocity of the single crystal Si 5. In more particular, the first modified example will be described with reference to Fig. 6.

[0045]

Fig. 6 is a graph showing the relationship of the synthetic acoustic velocity (synthetic acoustic velocity of the acoustic velocity of ScAlN and the acoustic velocity of SiO_2) and the ScAlN film thickness ratio (ScAlN/ScAlN+SiO_2) obtained when ScAlN having a Sc concentration of 15 atomic percent is used. From Fig. 6, it is found that as the ScAlN film thickness ratio is increased, the synthetic acoustic velocity is increased, and at a point Y in the graph, the synthetic acoustic velocity coincides with the acoustic velocity of the single crystal Si 5. That is, at the point Y in the graph, the acoustic velocity (v_1) of the single crystal Si 5 coincides with the synthetic acoustic velocity $(t_2v_2+t_3v_3)/(t_2+t_3)$ of the acoustic velocity (v_2) of ScAlN (piezoelectric thin film 8) and the acoustic velocity (v_3) of

SiO_2 (silicon oxide film 9). Hence, the acoustic velocity (v_{total}) of the piezoelectric resonator 1 is represented by the following equation (4).

[0046]

[Eq. 4]

$$v_{total} = \frac{t_1 v_1 + t_2 v_2 + t_3 v_3}{t_{total}} = \frac{t_1 v_1 + (t_2 + t_3) v_1}{t_{total}} = v_1$$

Equation (4)

(v_{total}: acoustic velocity of piezoelectric resonator, t_{total}: thickness of piezoelectric resonator, v_1: acoustic velocity of single crystal Si, t_1: thickness of single crystal Si, v_2: acoustic velocity of piezoelectric thin film, t_2: thickness of piezoelectric thin film, v_3: acoustic velocity of SiO_2, t_3: thickness of SiO_2)

[0047]

As shown by Equation (4), since being represented by $v_{total}=v_1$, the acoustic velocity (v_{total}) of the piezoelectric resonator is also not dependent on the thickness in this modified example. Hence, since the resonance frequency of Equation (1) is also not dependent on the thickness, the variation in resonance frequency caused by the variation in thickness is not likely to be generated.

[0048]

As described above, when the concentration of scandium

and/or the film thickness ratio of scandium to the silicon oxide film 9 is adjusted, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si can be made to coincide with the acoustic velocity thereof. As a result, the resonance frequency becomes not dependent on the thickness. That is, the variation in resonance frequency caused by the variation in thickness can be suppressed.

[0049]

Fig. 7 is a graph showing the relationship of the piezoelectric constant (d_{33}) and the scandium (Sc) concentration. From Fig. 7, it is found that the piezoelectric constant (d_{33}) shows the maximum value when the Sc concentration is approximately 40 atomic percent. In this case, a wideband resonator can be stably obtained. On the other hand, when the Sc concentration is high, as shown in Fig. 3, since the acoustic velocity of ScAlN (piezoelectric thin film 8) is decreased, the acoustic velocity described above may not be made to coincide with the acoustic velocity of the single crystal Si 5 in some cases.

[0050]

Hence, for example, as shown in Fig. 8, as is a second modified example of the first embodiment, a non-doped aluminum nitride layer 10 having a high acoustic velocity

may be further disposed on the upper surface of the second electrode 7. By the structure as described above, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 may be made to coincide with the acoustic velocity thereof.

[0051]

In addition, as is a third modified example of the first embodiment shown in Fig. 9, when a boron (B)-containing aluminum nitride layer 11 is further disposed on the upper surface of the second electrode 7, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 can be made to coincide with the acoustic velocity thereof. The reason for this is that when doping is performed using B, as shown in Fig. 10, as the dopant concentration is increased, the acoustic velocity is increased.

[0052]

In addition, since the temperature characteristics of the B-containing aluminum nitride (BAlN) are preferable, the temperature characteristics of the piezoelectric resonator 1 can also be improved.

[0053]

In addition, in this embodiment, although B is used as the dopant, an element is not particularly limited as long as capable of increasing the acoustic velocity of aluminum

nitride. As the element described above, for example, carbon may be mentioned by way of example. As shown in Fig. 10, it is found that in the case in which carbon (C) is used as the dopant, as the dopant concentration is increased, the acoustic velocity is also increased.

[0054]

Although the piezoelectric resonator 1 according to the first embodiment of the present invention is a resonator using the width spreading vibration, as is a piezoelectric resonator 21 according to a second embodiment shown in Fig. 11, a resonator using in-plane bending vibration may also be used. The piezoelectric resonator 21 described above includes a support portion 22 and an even number of vibrations arms. In addition, in this embodiment, two vibration arms 23a and 23b are provided.

[0055]

The plane of each of the vibration arms 23a and 23b has a long and thin rectangular shape having a length direction and a width direction. One end of each of the vibration arms 23a and 23b is connected to the support portion 22 and functions as a fixed end, and the other end is displaceable and functions as a free end. The two vibration arms 23a and 23b extend in parallel to each other and have the same length. When an alternating electric field is applied, the vibration arms 23a and 23b are each a vibrating body which

performs bending vibration in an in-plane bending vibration mode.

[0056]

The support portion 22 is connected to the short sides of the vibration arms 23a and 23b. The support portion 22 extends in the width direction of each of the vibration arms 23a and 23b. The support portion 22 supports each of the vibration arms 23a and 23b in the form of a cantilever.

[0057]

Fig. 12 is a cross-sectional view of the portion along the line B-B shown in Fig. 11. As shown in Fig. 12, the vibration arms 23a and 23b are each formed of a single crystal Si 5, first electrodes 6a and 6b, second electrodes 7a and 7b, and a piezoelectric thin film 8. In more particular, on the single crystal Si 5, the first electrodes 6a and 6b are formed. The first electrode 6a and the first electrode 6b face each other in a width direction with a gap provided therebetween. The piezoelectric thin film 8 is formed on the single crystal Si 5 so as to cover the first electrodes 6a and 6b. The second electrodes 7a and 7b are formed on the piezoelectric thin film 8. The second electrode 7a and the second electrode 7b face each other in a width direction with a gap provided therebetween.

[0058]

As an electrode material, for example, Mo, Ti, Al, Ru,

or Pt may be used. The first and the second electrodes 6a, 6b, 7a, and 7b each may be a single layer film or a multilayer film formed of at least one of the above materials. A seed layer may be provided between the single crystal Si 5 and each of the first electrodes 6a and 6b. By the structure as described above, the crystallinity of each of the first electrodes 6a and 6b can be improved. As a seed layer material, for example, AlN, Ti, or ScAlN may be used.

[0059]

In the second embodiment, by a method similar to that of the first embodiment, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si can be made to coincide with the acoustic velocity thereof. That is, the synthetic acoustic velocity can be made so as not to be dependent on the thickness.

[0060]

In addition, the resonance frequency of the in-plane bending vibrator which is the second embodiment can be represented by the following equation (5).

[0061]

[Eq. 5]

$$fr = \frac{\pi}{4\sqrt{3}} \frac{a}{l^2} \sqrt{\frac{2}{1+\sigma}} \sqrt{\frac{1}{\rho s_{33}^E}} = \frac{\pi}{4\sqrt{3}} \frac{a}{l^2} \sqrt{\frac{2}{1+\sigma}} v_{total} \quad \text{Equation (5)}$$

(fr: resonance frequency, l: length, a: width, σ: Poisson

ratio, ρ: density, S^E: elastic compliance, v_{total}: acoustic velocity of piezoelectric resonator)

[0062]

From Equation (5), it is found that at the resonance frequency of the in-plane bending vibrator, when the synthetic acoustic velocity is not dependent on the thickness, the resonance frequency is also not dependent on the thickness. Hence, in the in-plane bending vibrator, when the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 is made to coincide with the acoustic velocity thereof, the variation in resonance frequency caused by the variation in thickness can also be suppressed.

[0063]

A method for manufacturing the piezoelectric resonator according to the present invention comprises the steps of preparing the single crystal Si 5, forming the first electrode 6 on the single crystal Si 5, forming the piezoelectric thin film 8 from aluminum nitride on the first electrode 6, and forming the second electrode 7 on the piezoelectric thin film 8. In addition, in the step of forming the piezoelectric thin film 8 of the method for manufacturing the piezoelectric resonator according to the present invention, an element excluding nitrogen and aluminum is doped into aluminum nitride in advance so that

the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 is made to coincide with the acoustic velocity thereof.

[0064]

As a modified example of the second embodiment shown in Fig. 17, the piezoelectric thin film 8 may be formed on the single crystal Si 5 with a silicon oxide film 9 provided therebetween. In this case, by a method similar to that of the first modified example of the first embodiment, the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si 5 can be made to coincide with the acoustic velocity thereof. In addition, instead of the silicon oxide film 9, a silicon nitride film may also be formed.

[0065]

According to a method for manufacturing the piezoelectric resonator of the modified example of the second embodiment shown in Fig. 17, an electrically conductive film is formed by a CVD method or a sputtering method on the prepared single crystal Si 5. Next, by etching or the like, patterning of the electrically conductive film is performed. Accordingly, the first electrodes 6a and 6b are formed on the single crystal Si 5 so as to face each other with a gap provided therebetween. Subsequently, by using a sputtering method, a CVD method, or

the like, the silicon oxide film 9 is formed. Next, by an etching method, a CMP method, or the like, the silicon oxide film 9 is removed so as to expose the first electrodes 6a and 6b. Subsequently, the piezoelectric thin film 8 is formed on the first electrodes 6a and 6b and the silicon oxide film 9.

[0066]

Accordingly, since the step formed between the single crystal Si 5 and each of the first electrodes 6a and 6b can be filled with the silicon oxide film 9, the step can be made difficult to be generated in the piezoelectric thin film 8. As a result, the piezoelectric thin film 8 can be formed so that cracks and or voids are not likely to be formed therein. Hence, the elastic loss can be reduced, and furthermore, the Q value and the electromechanical coupling coefficient can be increased.

[0067]

Next, concrete examples will be described. Incidentally, the present invention is not limited to the following examples.

[0068]

(Example 1)

Under the following conditions, a width spreading vibrator was formed which had approximately the same structure as that of the piezoelectric resonator 1 according

to the first modified example of the first embodiment described above.

[0069]

Single crystal Si layer: resistivity: 1 mΩ·cm, n type (concentration: $7\times10^{19}/cm^3$), thickness: 10 μm

SiO_2 layer: 400 nm

Seed layer AlN (between lower electrode and SiO_2): 20 nm

Lower electrode Mo: 100 nm

Sc concentration of piezoelectric ScAlN: 25 atomic percent

Upper electrode Mo: 100 nm

[0070]

(Example 2)

Except that an in-plane bending vibrator was formed instead of the width spreading vibrator, no SiO_2 layer was provided, and the Sc concentration of the piezoelectric ScAlN was set to 38 atomic percent, a sample was formed in a manner similar to that of Example 1.

[0071]

(Example 3)

Except that a high acoustic velocity layer AlN having a thickness of 350 nm was laminated on the upper electrode, and the Sc concentration of the piezoelectric ScAlN was set to 38 atomic percent, a sample was formed in a manner similar to that of Example 1.

[0072]

(Example 4)

Except that AlN which was doped with B at a concentration of 15 atomic percent and which had a thickness of 250 nm was laminated on the upper electrode, and the Sc concentration of the piezoelectric ScAlN was set to 38 atomic percent, a sample was formed in a manner similar to that of Example 1.

[0073]

(Evaluation of Examples)

The variation in frequency of each of the samples thus formed was evaluated by the resonance frequency using an impedance analyzer. In addition, the thickness of the single crystal Si was measured by an optical thickness measurement apparatus.

[0074]

Hereinafter, the evaluation results are shown.

[0075]

(Example 1)

Fig. 13 is a graph showing the relationship of the variation in resonance frequency and the thickness of Si of the width spreading vibrator of Example 1. A variation in resonance frequency of Δfr=156 ppm/ΔSi=0.1 μm before Sc doping was significantly improved to Δfr=6 ppm/ΔSi=0.1 μm. In addition, since the heavily doped n-type Si was used, the

variation in frequency with the temperature was also significantly improved.

[0076]

(Example 2)

Fig. 14 is a graph showing the relationship of the variation in resonance frequency and the thickness of Si of the in-plane bending vibrator of Example 2. A variation in resonance frequency of Δfr=317 ppm/ΔSi=0.1 μm before Sc doping was significantly improved to Δfr=6 ppm/ΔSi=0.1 μm. In addition, since the heavily doped n-type Si was used, the variation in frequency with the temperature was also significantly improved.

[0077]

(Example 3)

Fig. 15 is a graph showing the relationship of the variation in resonance frequency and the thickness of Si of the width spreading vibrator of Example 3. A variation in resonance frequency of Δfr=156 ppm/ΔSi=0.1 μm before Sc doping was significantly improved to Δfr=0.2 ppm/ΔSi=0.1 μm. In addition, in Example 3, since Sc was doped at a high concentration, compared to a fractional bandwidth of 0.78% of Example 1, the fractional bandwidth was increased to 1.32%.

[0078]

(Example 4)

Fig. 16 is a graph showing the relationship of the variation in resonance frequency and the thickness of Si of the width spreading vibrator of Example 4. A variation in resonance frequency of Δfr=156 ppm/ΔSi=0.1 μm before Sc doping was significantly improved to Δfr=1 ppm/ΔSi=0.1 μm. In Example 4, since AlN was doped with B, the temperature characteristics were good as compared to those of Example 3, and the temperature characteristics of the vibrator were improved.

Reference Signs List

[0079]

1 piezoelectric resonator

2a, 2b support portion

3 vibration plate

4a, 4b connection portion

5 single crystal Si

5a upper surface

6, 6a, 6b first electrode

7, 7a, 7b second electrode

8 piezoelectric thin film

9 silicon oxide film

10 aluminum nitride layer

11 B-containing aluminum nitride layer

21 piezoelectric resonator

22 support portion

23a, 23b vibration arm

CLAIMS

[Claim 1]

A piezoelectric resonator comprising:

a single crystal Si;

a piezoelectric thin film formed from aluminum nitride and provided on the single crystal Si; and

a first and a second electrode provided so as to sandwich the piezoelectric thin film,

wherein the piezoelectric thin film formed from aluminum nitride is doped with an element excluding nitrogen and aluminum, and

a synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si substantially coincides with the acoustic velocity thereof.

[Claim 2]

The piezoelectric resonator according to Claim 1, wherein the doping is performed so that the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si is made to substantially coincide with the acoustic velocity thereof.

[Claim 3]

The piezoelectric resonator according to Claim 1 or 2, wherein the doping is performed using at least one type of element selected from the group consisting of scandium, yttrium, lutetium, and dysprosium.

[Claim 4]

The piezoelectric resonator according to any one of Claims 1 to 3, wherein the single crystal Si is doped with an n-type dopant, and the concentration of the n-type dopant is $1\times10^{9}/cm^{3}$ or more.

[Claim 5]

The piezoelectric resonator according to any one of Claims 1 to 4, further comprising a silicon oxide film layer disposed so as to be in contact with the first electrode or the second electrode.

[Claim 6]

The piezoelectric resonator according to any one of Claims 1 to 5, further comprising a dielectric film which has a high acoustic velocity as compared to that of the piezoelectric thin film formed from aluminum nitride doped with an element excluding nitrogen and aluminum and which is disposed so as to be in contact with the first electrode or the second electrode.

[Claim 7]

The piezoelectric resonator according to Claim 6, wherein the dielectric film having a high acoustic velocity is formed from aluminum nitride doped with at least one element of boron and carbon.

[Claim 8]

The piezoelectric resonator according to any one of

Claims 1 to 7, wherein the vibration mode is width spreading vibration or in-plane bending vibration.

[Claim 9]

A method for manufacturing the piezoelectric resonator according to any one of Claims 1 to 8, the method comprising the steps of:

preparing the single crystal Si;

forming the first electrode on the single crystal Si;

forming the piezoelectric thin film from aluminum nitride on the first electrode; and

forming the second electrode on the piezoelectric thin film,

wherein the step of forming the piezoelectric thin film includes a step of doping an element excluding nitrogen and aluminum into the aluminum nitride in advance so that the synthetic acoustic velocity of the acoustic velocities of the portions other than the single crystal Si is made to substantially coincide with the acoustic velocity thereof.