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### Method for manufacturing acoustic devices with improved performance

#### Abstract

A method for manufacturing an acoustic device includes providing a substrate, providing a bottom electrode over the substrate, providing a sacrificial layer on the bottom electrode, patterning the bottom electrode and the sacrificial layer, polishing the sacrificial layer such that a portion of the sacrificial layer remains on the bottom electrode, and removing the remaining portion of the sacrificial layer via a cleaning process such that a surface roughness of the bottom electrode is maintained. By performing the polishing such that a portion of the sacrificial layer remains on the bottom electrode and subsequently removing that portion of the sacrificial layer via a cleaning process that maintains the surface roughness of the bottom electrode, the subsequent growth of a piezoelectric layer on the bottom electrode can be substantially improved.

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## **Background/Summary**

**CROSS-REFERENCE TO RELATED APPLICATIONS** (1) This application is a continuation of U.S. patent application Ser. No. 17/361,698 filed on Jun. 29, 2021 and subsequently patented as U.S. Pat. No. 11,990,885 on May 21, 2024, wherein the entire contents of the foregoing application and patent are hereby incorporated by reference herein.

### **FIELD OF THE DISCLOSURE**

(1) The present disclosure is related to acoustic devices, and in particular to acoustic devices with improved performance and methods for manufacturing the same.

### **BACKGROUND**

(2) Acoustic devices include a piezoelectric layer in electrical contact with one or more electrodes. The performance of an acoustic device is in large part determined by the properties of the piezoelectric layer. These properties may include an orientation of the crystalline structure of the piezoelectric layer. Depositing a piezoelectric layer having a particular crystallographic orientation presents a large technical challenge. Using conventional processes, it has often been difficult to provide a piezoelectric layer having a desired crystallographic orientation. Accordingly, there is a need for acoustic devices having a piezoelectric layer with a precisely defined crystallographic orientation and methods for manufacturing the same.

### **SUMMARY**

(3) In one embodiment, a method for manufacturing an acoustic device includes providing a substrate, providing a bottom electrode over the substrate, providing a sacrificial layer on the bottom electrode, patterning the bottom electrode and the sacrificial layer, polishing the sacrificial layer such that a portion of the sacrificial layer remains on the bottom electrode, and removing the remaining portion of the sacrificial layer via a cleaning process such that a surface roughness of the bottom electrode is maintained. By performing the polishing such that a portion of the sacrificial layer remains on the bottom electrode and subsequently removing that portion of the sacrificial layer via a cleaning process that maintains the surface roughness of the bottom electrode, the subsequent growth of a piezoelectric layer on the bottom electrode can be substantially improved.

(4) In one embodiment, an acoustic device includes a substrate, a bottom electrode, a seed layer, a piezoelectric layer, and a top electrode. The bottom electrode includes a top surface, which has a roughness between 0.3 nm average roughness (Ra) and 2 nm Ra. The seed layer is on the top surface of the bottom electrode. The piezoelectric layer is on the seed layer. The top electrode is on the piezoelectric layer. By providing the bottom electrode having the top surface with a roughness between 0.3 nm Ra and 2 nm Ra, the seed layer and the piezoelectric layer may have one or more desired properties such as a desired c-axis tilt that would not otherwise be achievable. Accordingly, the performance of the acoustic device may be improved.

(5) In another aspect, any of the foregoing aspects individually or together, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various features and elements as disclosed herein may be combined with one or more other

disclosed features and elements unless indicated to the contrary herein.

(6) Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

#### BRIEF DESCRIPTION OF THE DRAWING FIGURES

(7) The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

(8) FIG. 1 is a flow chart illustrating a method for manufacturing an acoustic device according to one embodiment of the present disclosure.

(9) FIGS. 2A through 2M illustrate a method for manufacturing an acoustic device according to one embodiment of the present disclosure.

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## Description

### DETAILED DESCRIPTION

(1) The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

(2) It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present disclosure. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

(3) It will be understood that when an element such as a layer, region, or substrate is referred to as being “on” or extending “onto” another element, it can be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” or extending “directly onto” another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being “over” or extending “over” another element, it can be directly over or extend directly over the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly over” or extending “directly over” another element, there are no intervening elements present. It will also be understood that when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no intervening elements present.

(4) Relative terms such as “below” or “above” or “upper” or “lower” or “horizontal” or “vertical” may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

(5) The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates

otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes,” and/or “including” when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

(6) Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

(7) Embodiments are described herein with reference to schematic illustrations of embodiments of the disclosure. As such, the actual dimensions of the layers and elements can be different, and variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are expected. For example, a region illustrated or described as square or rectangular can have rounded or curved features, and regions shown as straight lines may have some irregularity. Thus, the regions illustrated in the figures are schematic and their shapes are not intended to illustrate the precise shape of a region of a device and are not intended to limit the scope of the disclosure. Additionally, sizes of structures or regions may be exaggerated relative to other structures or regions for illustrative purposes and, thus, are provided to illustrate the general structures of the present subject matter and may or may not be drawn to scale. Common elements between figures may be shown herein with common element numbers and may not be subsequently re-described.

(8) As discussed above, certain crystallographic orientations of a piezoelectric layer may provide beneficial effects in the performance of an acoustic device such as a bulk acoustic wave (BAW) resonator. Principles of the present disclosure relate to methods for obtaining a desired crystallographic orientation of a piezoelectric layer with a high degree of precision. The principles of the present disclosure are applicable to any type of acoustic devices such as surface acoustic wave (SAW) resonators, BAW resonators, and the like.

(9) FIG. 1 is a flow diagram illustrating a method for manufacturing an acoustic device **10** according to one embodiment of the present disclosure. FIGS. 2A through 2M are cross-sectional views of the acoustic device **10** throughout the manufacturing process, and thus are discussed together with FIG. 1. First, a substrate **12** is provided (step **100** and FIG. 2A). The substrate **12** may be any suitable material and thickness for supporting the resultant acoustic device **10**. In one embodiment, the substrate **12** comprises silicon and has a thickness between 150  $\mu\text{m}$  and 725  $\mu\text{m}$ . A reflector structure **14** is provided on the substrate **12** (step **102** and FIG. 2B). The reflector structure **14** is shown as a Bragg reflector including alternating layers of materials. In one embodiment, the reflector structure **14** comprises alternating layers of silicon dioxide (shown as **14A**), aluminum nitride (shown as **14B**), and tungsten (shown as **14C**). While a particular reflector structure **14** is shown for purposes of example, those skilled in the art will appreciate that any reflector structure **14** may be used without departing from the principles of the present disclosure. In some embodiments, the reflector structure **14** may be omitted and replaced, for example, with an air cavity, as in the case of a membrane or air-gap thin-film bulk acoustic resonator (FBAR), to which the principles of the present disclosure can be readily applied. The reflector structure **14** may be provided by any suitable deposition process, which may include any number of steps. Details of providing the reflector structure **14** will be readily appreciated by those skilled in the art and thus are not discussed herein.

(10) A bottom electrode **16** is provided on the reflector structure **14** (step **104** and FIG. 2C). The bottom electrode **16** may comprise any number of layers of material. In one embodiment, the bottom electrode **16** comprises a first layer of aluminum copper (shown as **16A**) and a second layer of tungsten (shown as **16B**). However, the bottom electrode **16** may comprise any number of

suitable materials. When the reflector structure **14** is not provided, the bottom electrode **16** may be provided directly on the substrate **12** or on any number of different intervening layers on the substrate **12**. A thickness of the bottom electrode **16** may be between 500 Angstroms (Å) and 4000 Å. In particular, a thickness of the first layer of aluminum copper may be between 250 Å and 2000 Å, and a thickness of the second layer of tungsten may be between 250 Å and 2000 Å. Notably, the present disclosure contemplates the use of any discrete point or sub-range within the exemplary ranges discussed herein for any of the layers.

(11) A sacrificial layer **18** is provided on the bottom electrode **16** (step **106** and FIG. **2D**). In one embodiment, the sacrificial layer **18** comprises amorphous or polycrystalline aluminum nitride, however, any suitable material may be used for the sacrificial layer **18** without departing from the principles herein. Notably, the sacrificial layer **18** is grown to a thickness  $t$  that is between 200 Å and 2000 Å. As discussed in detail below, providing the sacrificial layer **18** such that the thickness  $t$  is between 200 Å and 2000 Å provides a buffer that protects the bottom electrode **16** during a polishing process so as to maintain a surface roughness of the bottom electrode **16** that promotes the growth of a piezoelectric layer having a desired crystallographic orientation.

(12) A cap layer **20** is provided on the sacrificial layer **18** (step **108** and FIG. **2E**). In one embodiment, the cap layer **20** comprises silicon dioxide, however, any suitable material may be used for the cap layer **20**. A thickness of the cap layer **20** may be between 100 Å and 1000 Å.

(13) The cap layer **20**, the sacrificial layer **18**, and the bottom electrode **16** are then patterned (step **110** and FIG. **2F**). The cap layer **20**, the sacrificial layer **18**, and the bottom electrode **16** may be patterned by any suitable process such as a photolithography patterning process. The details of patterning the cap layer **20**, the sacrificial layer **18**, and the bottom electrode **16** will be readily appreciated by those skilled in the art and thus are not discussed in detail herein.

(14) A planarization oxide **22** is provided on the exposed portions of the reflector structure **14**, the bottom electrode **16**, the sacrificial layer **18**, and the cap layer **20** (step **112** and FIG. **2G**). In one embodiment, the planarization oxide **22** comprises silicon dioxide. The planarization oxide **22** may have a thickness between 200 Å and 4400 Å. Notably, the planarization oxide **22** may be provided having a thickness calibrated to provide a certain amount of buffer material between a top surface thereof and the bottom electrode **16** such that the top surface of the planarization oxide **22** is used for calibration during a polishing process as discussed below.

(15) The planarization oxide **22** and the cap layer **20** are patterned (step **114** and FIG. **2H**) such that the sacrificial layer **18** is exposed through one or more openings in the planarization oxide **22**. The planarization oxide **22** and the sacrificial layer **18** are then polished (step **116** and FIG. **2I**). The planarization oxide **22** and the sacrificial layer **18** may be polished using any suitable process. In one embodiment, the planarization oxide **22** and the sacrificial layer **18** are polished using a chemical-mechanical polishing (CMP) process. Notably, the polishing is performed such that a portion of the sacrificial layer **18** remains on the bottom electrode **16**. In a conventional manufacturing process for an acoustic device, the sacrificial layer **18** is polished all the way through such that a top surface of the bottom electrode **16** is also polished. This results in a very smooth top surface of the bottom electrode **16**, which may be disadvantageous for subsequent growth of a piezoelectric layer. By leaving a portion of the sacrificial layer **18** on the bottom electrode **16**, the surface roughness of the bottom electrode **16** can be maintained at a desired level, leading to improved control over the subsequent growth of a piezoelectric layer as discussed below. Due to the limited selectivity of CMP processes, the thickness of the sacrificial layer **18** and the planarization oxide **22** are adjusted such as to maintain the portion of the sacrificial layer **18** on the bottom electrode **16** during the process. However, this is not required if a polishing process with a very high degree of selectivity is developed and/or used.

(16) The remaining portion of the sacrificial layer **18** is removed in a cleaning process (step **118** and FIG. **2J**). Any suitable cleaning process which maintains the surface roughness of the bottom electrode **16** may be used. In one embodiment, a scrubber cleaning process is used to remove the

remaining portion of the sacrificial layer **18** while maintaining the surface roughness of the bottom electrode **16**. The cleaning process may etch away the remaining portion of the sacrificial layer **18** rather than mechanically polishing it away, which may prevent unnecessary smoothing of the surface of the bottom electrode **16**.

(17) The roughness of the surface of the bottom electrode **16** after removal of the sacrificial layer **18** is important for determining the crystallographic orientation and quality of a subsequently grown piezoelectric layer on the bottom electrode **16**. If the surface of the bottom electrode **16** is too smooth (e.g., root mean square (RMS) average of profile height deviations from the mean line less than 2 nm), particles contacting the surface of the bottom electrode **16** during a subsequent deposition step will shift in position as they contact the surface and grow in undesired crystallographic orientations. The surface roughness of the bottom electrode **16** is at a desired amount when deposited. Accordingly, by tailoring the manufacturing process to minimally degrade the surface roughness of the bottom electrode **16** as applied, desired qualities of the subsequently grown piezoelectric layer can be maintained. In various embodiments, the principles discussed herein enable a surface roughness of the bottom electrode **16** between 0.3 nm Ra and 2 nm Ra after removal of the sacrificial layer **18**. In some embodiments, an additional step which includes increasing the surface roughness of the bottom electrode **16** (e.g., via a process such as ion milling, sputtering, etc.) may be performed after removal of the sacrificial layer **18**. Notably, the present disclosure contemplates the use of any discrete point or sub-range within the exemplary given range for the surface roughness of the bottom electrode **16** herein.

(18) A seed layer **24** is grown on the bottom electrode **16** (step **120** and FIG. 2K). In one embodiment, the seed layer **24** comprises aluminum nitride, however, the seed layer **24** can comprise any suitable piezoelectric material. Notably, the seed layer **24** is grown in an off-axis deposition process wherein deposited particles impact the bottom electrode **16** at a predetermined angle with respect to a normal angle from a surface of the substrate **12**. Depositing the seed layer **24** in this manner results in a desired c-axis tilt of the seed layer **24**. The surface roughness of the bottom electrode **16** is crucial for providing said c-axis tilt of the seed layer **24** at a desired amount. As discussed above, if the surface of the bottom electrode **16** is too smooth, particles contacting the bottom electrode **16** during deposition can shift in position as they glide along the surface of the bottom electrode **16**, leading to unpredictable and/or undesired crystalline growth patterns. In one embodiment, a c-axis tilt of the seed layer **24** with respect to a surface plane of the bottom electrode **16** is between 8° and 35°. A thickness of the seed layer **24** may be between 900 Å and 1500 Å. Notably, the present disclosure contemplates the use of any discrete point or sub-range within the exemplary range for the c-axis tilt of the seed layer **24** herein.

(19) A piezoelectric layer **26** is grown on the seed layer **24** (step **122** and FIG. 2L). In one embodiment, the piezoelectric layer **26** comprises aluminum nitride, however, the piezoelectric layer **26** may comprise any suitable piezoelectric material. In one embodiment, the piezoelectric layer **26** is grown in a normal-axis deposition process wherein deposited particles impact the seed layer **24** at a normal angle with respect to a surface plane of a normal angle from a surface of the substrate **12**. In other embodiments, the piezoelectric layer **26** may be grown in an off-axis deposition process wherein deposited particles impact the seed layer **24** at a predetermined angle with respect to a normal angle from a surface of the substrate **12**. This angle may be the same or different than the angle used for the deposition process of the seed layer **24**. Due to the crystalline orientation of the seed layer **24** however, the piezoelectric layer **26** also grows having a c-axis tilt that is not normal to the surface plane of the bottom electrode **16**. In one embodiment, a c-axis tilt of the piezoelectric layer **26** with respect to a surface plane of the bottom electrode **16** is between 8° and 35°. A thickness of the piezoelectric layer **26** may be between 2000 Å and 5000 Å. Notably, the present disclosure contemplates the use of any discrete point or sub-range within the exemplary range for the c-axis tilt of the piezoelectric layer **26** herein.

(20) A top electrode **28** is provided on the piezoelectric layer **26** (step **124** and FIG. 2M). The top

electrode **28** may be provided by any suitable deposition and/or patterning steps. In one embodiment, the top electrode **28** may comprise tungsten, or multiple layers including tungsten and one or more other suitable metals.

(21) Due to the maintenance of the surface roughness of the bottom electrode **16** and the off-axis deposition processes used for the seed layer **24** (and in some embodiments the piezoelectric layer **26**), the resulting piezoelectric layer **26** has a desired crystallographic orientation, specifically with regard to the c-axis tilt thereof. The resulting acoustic device **10** may thus have improved performance in a number of different domains. For example, the principles discussed herein may enable an inductance of the acoustic device **10** greater than 0.5 times the value reflection coefficient imaginary component. Further, the principles discussed herein may enable a sensitivity greater than 84000 MHz/ng/sq $\mu$ m.

(22) The resulting acoustic device **10** may be used in a variety of applications. In various embodiments, the acoustic device **10** can be used as a resonator, which may provide functions such as sensing one or more desired signals (e.g., in liquid environments). Notably, the acoustic device **10** discussed herein is merely exemplary. The principles of the present disclosure can apply to any acoustic device wherein a piezoelectric layer contacts an electrical contact.

(23) It is contemplated that any of the foregoing aspects, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various embodiments as disclosed herein may be combined with one or more other disclosed embodiments unless indicated to the contrary herein.

(24) Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

## Claims

1. A method for manufacturing an acoustic device, the method comprising: providing a substrate; providing a bottom electrode over the substrate; providing a sacrificial layer on the bottom electrode; patterning the bottom electrode and the sacrificial layer; removing the sacrificial layer; and increasing a surface roughness of the bottom electrode after removal of the sacrificial layer to provide a surface roughness value between 0.3 nm Ra and 2 nm Ra.
2. The method of claim 1, wherein the removing of the sacrificial layer comprises polishing the sacrificial layer such that a portion of the sacrificial layer re-mains on the bottom electrode, followed by removing a remaining portion of the sacrificial layer from the bottom electrode via a cleaning process.
3. The method of claim 1, further comprising: providing a seed layer on the bottom electrode; and providing a piezoelectric layer on the seed layer.
4. The method of claim 3, wherein a c-axis tilt of the piezoelectric layer is between 8° and 35°.
5. The method of claim 1 wherein the sacrificial layer is provided having a thickness between 300 Å and 2000 Å.
6. The method of claim 1, further comprising providing a cap layer on the sacrificial layer before patterning the bottom electrode and the sacrificial layer.
7. The method of claim 1, further comprising providing a planarization oxide on the exposed portions of the bottom electrode and the sacrificial layer before polishing the bottom electrode and the sacrificial layer.
8. An acoustic device comprising: a bottom electrode, the bottom electrode comprising a top surface having a roughness between 0.3 nm Ra and 2 nm Ra; a seed layer on the top surface of the bottom electrode; a piezoelectric layer on the seed layer, wherein a c-axis tilt of the piezoelectric layer is between 8° and 35° relative to a plane of the top surface of the bottom electrode; and a top electrode on the piezoelectric layer.



9. The acoustic device of claim 8, further comprising a reflector structure underlying the bottom electrode, with the bottom electrode being arranged between the reflector structure and the seed layer.
10. The acoustic device of claim 8, wherein the reflector structure comprises alternating layers of aluminum nitride, silicon dioxide, and tungsten.
11. The acoustic device of claim 8, further comprising: a substrate; and an air cavity arranged between the substrate and the bottom electrode.
12. The acoustic device of claim 8, wherein: the bottom electrode comprises a layer of aluminum copper and a layer of tungsten on the layer of aluminum copper; and the seed layer and the piezoelectric layer comprise aluminum nitride.
13. The acoustic device of claim 8, wherein the seed layer comprises a piezoelectric material.
14. The acoustic device of claim 8, comprising an inductance greater than 0.5 times a value reflection coefficient imaginary component of the acoustic device.
15. The acoustic device of claim 8, comprising a sensitivity greater than 84000 MHz/ng/sq $\mu$ m.
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