SUMMARY OF CERTAIN INVENTIVE ASPECTS

[0006] The innovations described in the claims each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of the claims, some prominent features of this disclosure will now be briefly described.

[0007] One ~~aspect~~ example of this disclosure is an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, high velocity layers on opposing sides of the piezoelectric layer, and a low velocity layer positioned between the piezoelectric layer and a first high velocity layer of the high velocity layers. The low velocity layer has a lower acoustic velocity than the high velocity layers. The acoustic velocity is the speed of sound of a shear wave propagating in a solid. The acoustic wave device is configured to generate a boundary acoustic wave such that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer.

[0008] Each of the high velocity layers can have a higher acoustic velocity than a velocity of the boundary acoustic wave. The velocity of the boundary acoustic wave can be in a range from 2500 meters per second to 4800 meters per second. The velocity of the boundary acoustic wave can be in a range from 4100 meters per second to 4800 meters per second.

[0009] The low velocity layer can include silicon dioxide. The high velocity layers can be silicon layers.

[0010] At least one of the high velocity layers can be a silicon layer. At least one of the high velocity layers can include at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel. The high velocity layers can be made of the same material as each other.

[0011] The boundary acoustic wave has a wavelength of λ. With a thickness of at least 1λ, the boundary acoustic wave can be confined at the boundary of the piezoelectric layer and the low velocity layer. At least one of the high velocity layers can have a thickness in a range from 1λ to 10λ. At least one of the high velocity layers can have a thickness in a range from 1λ to 5λ. In some instances, one or both of the high velocity layers can have a thickness of greater than 10λ. The piezoelectric layer can have a thickness of less than 2λ. The piezoelectric layer can be a lithium tantalate layer. The piezoelectric layer can be a lithium niobate layer.

[0012] Another ~~aspect~~ example of this disclosure is a radio frequency module that includes an acoustic wave filter configured to filter a radio frequency signal and a radio frequency switch coupled to the acoustic wave filter. The radio frequency switch is packaged with the acoustic wave filter. The acoustic wave filter includes an acoustic wave device including a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, high velocity layers on opposing sides of the piezoelectric layer, and a low velocity layer disposed between the piezoelectric layer and a first high velocity layer of the high velocity layers. The low velocity layer has a lower acoustic velocity than the high velocity layers. The acoustic wave device is configured to generate a boundary acoustic wave such that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer.

[0013] The radio frequency module can include a power amplifier, in which the radio frequency switch is configured to selectively electrically connect an output of the power amplifier to the acoustic wave filter. The radio frequency module can include an antenna port, in which the radio frequency switch is configured to selectively electrically connect the acoustic wave filter to an antenna port of the radio frequency module.

[0014] Another ~~aspect~~ example of this disclosure is a method of filtering a radio frequency signal with an acoustic wave filter. The method includes providing a radio frequency signal to an acoustic wave filter and filtering the radio frequency signal with the acoustic wave filter. The acoustic wave filter includes an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, high velocity layers on opposing sides of the piezoelectric layer, a low velocity layer positioned between the piezoelectric layer and a first high velocity layer of the high velocity layers. The low velocity layer having a lower acoustic velocity than the high velocity layers. The acoustic wave device generating a boundary acoustic wave such that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer.

[0015] The high velocity layers can be silicon layers and the low velocity layer can be a silicon dioxide layer. The piezoelectric layer can be a lithium niobate layer or a lithium tantalate layer.

[0016] Another ~~aspect~~ example of this disclosure is an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer,

high velocity layers on opposing side of the piezoelectric layer, and a temperature compensation

layer positioned between the first high velocity layer and the piezoelectric layer. The high velocity layers include a first high velocity layer having a first acoustic velocity and a second high velocity layer having a second acoustic velocity. The acoustic wave device is configured to generate a boundary acoustic wave having a velocity that is less than both the first acoustic velocity and the second acoustic velocity.

[0017] The first acoustic velocity can be substantially the same as the second acoustic velocity. The first acoustic velocity can be different than the second acoustic velocity.

[0018] The first high velocity layer can be a silicon layer. The second high velocity layer can be a second silicon layer. The first high velocity layer can include at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel. The piezoelectric layer can be either a lithium tantalate layer or a lithium niobate layer. The temperature compensation layer can include silicon dioxide.

[0019] The boundary acoustic wave has a wavelength of λ. The first high velocity layer can have a thickness in a range from 1λ to 10λ. The piezoelectric layer can have a thickness of less than 2λ.

[0020] The interdigital transducer electrode is can be contact with the piezoelectric layer on a side of the piezoelectric layer facing the temperature compensation layer. The interdigital transducer electrode can be in contact with the piezoelectric layer on a side of the piezoelectric layer that is opposite to the temperature compensation layer.

[0021] Another ~~aspect~~ example of this disclosure is an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, silicon layers on opposing sides of the piezoelectric layer, and a silicon dioxide layer disposed between one of the silicon layers and the piezoelectric layer. The acoustic wave device is configured to generate a boundary acoustic wave at an interface of the piezoelectric layer and the interdigital transducer electrode.

[0022] The boundary acoustic wave has a wavelength of λ. The silicon layers can each have a thickness in a range from λ to 10λ. The piezoelectric layer can have a thickness of no greater than 2λ.

[0023] The piezoelectric layer can be a lithium tantalate layer. The piezoelectric layer can be a lithium niobate layer.

[0024] The interdigital transducer electrode can be on a side of the piezoelectric layer facing the silicon dioxide layer. The interdigital transducer electrode can be on a side of the piezoelectric layer opposite to the silicon dioxide layer.

[0025] Another ~~aspect~~ example of this disclosure is an acoustic wave filter comprising an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, silicon layers on opposing sides of the piezoelectric layer, and a silicon dioxide layer disposed between one of the silicon layers and the piezoelectric layer. The acoustic wave device is configured to generate a boundary acoustic wave. The acoustic wave filter is configured to filter a radio frequency signal.

[0026] ~~Another~~ A first aspect of this disclosure is an acoustic wave device assembly that includes a first die, ~~and~~ a second die stacked with the first die and a dielectric layer disposed between the first die and the second die. The first die includes a first acoustic wave device configured to generate a boundary acoustic wave. The first acoustic wave device includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, and high acoustic velocity layers on opposing sides of the piezoelectric layer. The high acoustic velocity layers each have an acoustic velocity that is greater than a velocity of the boundary acoustic wave. The second die includes a second acoustic wave device configured to generate a second boundary acoustic wave.

[0026a] A second aspect of this disclosure is an acoustic wave device assembly that includes a first die, a second die stacked with the first die and an air gap between the first die and the second die. The first die includes a first acoustic wave device configured to generate a boundary acoustic wave. The first acoustic wave device includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, and high acoustic velocity layers on opposing sides of the piezoelectric layer. The high acoustic velocity layers each have an acoustic velocity that is greater than a velocity of the boundary acoustic wave. The second die includes a second acoustic wave device configured to generate a second boundary acoustic wave.

[0027] The acoustic wave device assembly can include a third die stacked with the first die and the second die, in which the third die can includes a third acoustic wave device configured to generate a third boundary acoustic wave.

[0028] The first acoustic wave device can include a temperature compensation layer disposed between the piezoelectric layer and a first high acoustic velocity layer of the high acoustic velocity layers.

[0029] A first high acoustic velocity layer of the high acoustic velocity layers can be a silicon layer. A first high acoustic velocity layer of the high acoustic velocity layers can include at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel.

[0030] The first acoustic wave device can be included in a first acoustic wave filter, and the second acoustic wave device can be included in a second acoustic wave filter.

[0031] The acoustic wave device assembly can include a via extending through the first die. The acoustic wave device assembly can include a wire bond extending from the second die.

[0032] The first die can be electrically isolated from the second die. The acoustic wave device assembly can include an air gap between the first die and the second die. The acoustic wave device assembly can include a dielectric material disposed between the first die and the second die. The acoustic wave device assembly can include a dielectric material and a metal shield disposed between the first die and the second die.

[0033] The second acoustic wave device can include a second piezoelectric layer, a second interdigital transducer electrode on the second piezoelectric layer, and second high acoustic velocity layers on opposing sides of the second piezoelectric substrate, in which the second high acoustic velocity layers each have an acoustic velocity that is greater than a velocity of the second boundary acoustic wave.

[0034] Another ~~aspect~~ example of this disclosure is a radio frequency module with acoustic wave filters. The radio frequency module includes a first acoustic wave filter configured to filter a first radio frequency signal, a second acoustic wave filter configured to filter a second radio frequency signal, and a package enclosing the first acoustic wave filter and the second acoustic wave filter. The first acoustic wave filter includes a first acoustic wave device on a first die and configured to generate a boundary acoustic wave. The first acoustic wave device includes a piezoelectric layer and high acoustic velocity layers on opposing sides of the piezoelectric layer, in which the high acoustic velocity layers each have an acoustic velocity that is greater than a velocity of the boundary acoustic wave. The second acoustic wave filter including a second acoustic wave device on a second die and configured to generate a second boundary acoustic wave. The second die is stacked with the first die.

[0035] A thickness of the radio frequency module can be less than 300 micrometers.

[0036] A duplexer can include the first acoustic wave filter and the second acoustic wave filter.

[0037] The radio frequency module can include a radio frequency switch coupled to the first acoustic wave filter and the second acoustic wave filter, in which the radio frequency switch being enclosed within the package.

[0038] Another aspect of this disclosure is a wireless communication device that includes an antenna and acoustic wave filters in communication with the antenna. The

WHAT IS CLAIMED IS:

1. An acoustic wave device comprising:

a piezoelectric layer;

an interdigital transducer electrode on the piezoelectric layer;

high velocity layers on opposing sides of the piezoelectric layer; and

a low velocity layer positioned between the piezoelectric layer and a first high velocity layer of the high velocity layers, the low velocity layer having a lower acoustic velocity than the high velocity layers, the acoustic velocity of the low velocity layer being a speed of sound of a shear wave propagating in the low velocity layer, and the acoustic wave device being configured to generate a boundary acoustic wave such that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer.

2. The acoustic wave device of claim 1 wherein each of the high velocity layers has a higher acoustic velocity than a velocity of the boundary acoustic wave.

3. The acoustic wave device of claim 1 wherein the low velocity layer includes silicon dioxide.

4. The acoustic wave device of claim 3 wherein the high velocity layers are silicon layers.

5. The acoustic wave device of claim 1 wherein at least one of the high velocity layers is a silicon layer.

6. The acoustic wave device of claim 1 wherein at least one of the high velocity layers includes at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel.

7. The acoustic wave device of claim 1 wherein the piezoelectric layer is a lithium tantalate layer.

8. The acoustic wave device of claim 1 wherein the piezoelectric layer is a lithium niobate layer.

9. The acoustic wave device of claim 1 wherein the high velocity layers are made of the same material as each other.

10. The acoustic wave device of claim 1 wherein the boundary acoustic wave has a wavelength of λ and at least one of the high velocity layers has a thickness in a range from 1λ to 10λ.

11. The acoustic wave device of claim 1 wherein the acoustic wave device has a thickness in a range from 10 micrometers (um) to 100 um.

12. The acoustic wave device of claim 1 wherein the boundary acoustic wave has a wavelength of λ and the piezoelectric layer has a thickness of less than 2λ.

13. The acoustic wave device of claim 1 wherein a velocity of the boundary acoustic wave is in a range from 2500 meters per second to 4800 meters per second.

14. The acoustic wave device of claim 1 wherein a velocity of the boundary acoustic wave is in a range from 4100 meters per second to 4800 meters per second.

15. A radio frequency module comprising:

an acoustic wave filter configured to filter a radio frequency signal, the acoustic wave filter including an acoustic wave device including a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, high velocity layers on opposing sides of the piezoelectric layer, and a low velocity layer disposed between the piezoelectric layer and a first high velocity layer of the high velocity layers, the low velocity layer having a lower acoustic velocity than the high velocity layers, and the acoustic wave device being configured to generate a boundary acoustic wave such

that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer; and

a radio frequency switch coupled to the acoustic wave filter, the radio frequency switch being packaged with the acoustic wave filter.

16. The radio frequency module of claim 15 further comprising a power amplifier, the radio frequency switch configured to selectively electrically connect an output of the power amplifier to the acoustic wave filter.

17. The radio frequency module of claim 15 further comprising an antenna port, the radio frequency switch configured to selectively electrically connect the acoustic wave filter to an antenna port of the radio frequency module.

18. A method of filtering a radio frequency signal with an acoustic wave filter, the method comprising:

providing a radio frequency signal to an acoustic wave filter; and

filtering the radio frequency signal with the acoustic wave filter, the acoustic wave filter including an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, high velocity layers on opposing sides of the piezoelectric layer, a low velocity layer positioned between the piezoelectric layer and a first high velocity layer of the high velocity layers, the low velocity layer having a lower acoustic velocity than the high velocity layers, and the acoustic wave device generating a boundary acoustic wave such that acoustic energy is concentrated at a boundary of the piezoelectric layer and the low velocity layer .

19. The method of claim 18 wherein the high velocity layers are silicon layers and the low velocity layer is a silicon dioxide layer.

20. The method of claim 19 wherein the piezoelectric layer is a lithium niobate layer or a lithium tantalate layer.

~~21. An acoustic wave device comprising:~~

~~a piezoelectric layer;~~

~~an interdigital transducer electrode on the piezoelectric layer;~~

~~high velocity layers on opposing side of the piezoelectric layer, the high velocity layers including a first high velocity layer having a first acoustic velocity and a second high velocity layer having a second acoustic velocity; and~~

~~a temperature compensation layer positioned between the first high velocity layer and the piezoelectric layer, the acoustic wave device being configured to generate a boundary acoustic wave having a velocity that is less than both the first acoustic velocity and the second acoustic velocity.~~

~~22. The acoustic wave device of claim 21 wherein the first acoustic velocity is substantially the same as the second acoustic velocity.~~

~~23. The acoustic wave device of claim 21 wherein the first acoustic velocity is different than the second acoustic velocity.~~

~~24. The acoustic wave device of claim 21 wherein the first high velocity layer is a silicon layer.~~

~~25. The acoustic wave device of claim 24 wherein the second high velocity layer is a second silicon layer.~~

~~26. The acoustic wave device of claim 21 wherein the first high velocity layer includes at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel.~~

~~27. The acoustic wave device of claim 21 wherein the piezoelectric layer is either a lithium tantalate layer or a lithium niobate layer.~~

~~28. The acoustic wave device of claim 21 wherein the temperature compensation layer includes silicon dioxide.~~

29. The acoustic wave device of claim 21 wherein the boundary acoustic wave has a wavelength of λ and the first high velocity layer has a thickness in a range from 1λ to 10λ.

30. The acoustic wave device of claim 21 wherein the interdigital transducer electrode is in contact with the piezoelectric layer on a side of the piezoelectric layer facing the temperature compensation layer.

31. The acoustic wave device of claim 21 wherein the interdigital transducer electrode is in contact with the piezoelectric layer on a side of the piezoelectric layer that is opposite to the temperature compensation layer.

32. The acoustic wave device of claim 21 wherein the boundary acoustic wave has a wavelength of λ and the piezoelectric layer has a thickness of less than 2λ.

33. An acoustic wave device comprising:

a piezoelectric layer;

an interdigital transducer electrode on the piezoelectric layer;

silicon layers on opposing sides of the piezoelectric layer; and

a silicon dioxide layer disposed between one of the silicon layers and the piezoelectric layer, the acoustic wave device being configured to generate a boundary acoustic wave at an interface of the piezoelectric layer and the interdigital transducer electrode.

34. The acoustic wave device of claim 33 wherein the boundary acoustic wave has a wavelength of λ and the silicon layers each have a thickness in a range from λ to 10λ.

35. The acoustic wave device of claim 34 wherein the boundary acoustic wave has a wavelength of λ and the piezoelectric layer has a thickness of no greater than 2λ.

~~36. The acoustic wave device of claim 33 wherein the piezoelectric layer is a lithium tantalate layer.~~

~~37. The acoustic wave device of claim 33 wherein the piezoelectric layer is a lithium niobate layer.~~

~~38. The acoustic wave device of claim 33 wherein the interdigital transducer electrode is on a side of the piezoelectric layer facing the silicon dioxide layer.~~

~~39. The acoustic wave device of claim 33 wherein the interdigital transducer electrode is on a side of the piezoelectric layer opposite to the silicon dioxide layer.~~

~~40. An acoustic wave filter comprising an acoustic wave device that includes a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, silicon layers on opposing sides of the piezoelectric layer, and a silicon dioxide layer disposed between one of the silicon layers and the piezoelectric layer, the acoustic wave device being configured to generate a boundary acoustic wave, and the acoustic wave filter configured to filter a radio frequency signal.~~

~~41.~~1. An acoustic wave device assembly comprising:

a first die including a first acoustic wave device configured to generate a boundary acoustic wave, the first acoustic wave device including a piezoelectric layer, an interdigital transducer electrode on the piezoelectric layer, and high acoustic velocity layers on opposing sides of the piezoelectric layer, the high acoustic velocity layers each having an acoustic velocity that is greater than a velocity of the boundary acoustic wave; ~~and~~

a second die stacked with the first die, the second die including a second acoustic wave device configured to generate a second boundary acoustic wave; and

a dielectric layer disposed between the first die and the second die.

~~42.~~2. The acoustic wave device assembly of claim ~~4~~1 further comprising a third die stacked with the first die and the second die, the third die including a third acoustic wave device configured to generate a third boundary acoustic wave.

~~43.~~3. The acoustic wave device assembly of claim ~~4~~1 wherein the first acoustic wave device further includes a temperature compensation layer disposed between the piezoelectric layer and a first high acoustic velocity layer of the high acoustic velocity layers.

~~44.~~4. The acoustic wave device assembly of claim ~~4~~1 wherein a first high acoustic velocity layer of the high acoustic velocity layers is a silicon layer.

~~45.~~5. The acoustic wave device assembly of claim ~~4~~1 wherein a first high acoustic velocity layer of the high acoustic velocity layers includes at least one of silicon nitride, aluminum nitride, diamond, quartz, or spinel.

~~46.~~6. The acoustic wave device assembly of claim ~~4~~1 wherein the first acoustic wave device is included in a first acoustic wave filter and the second acoustic wave device is included in a second acoustic wave filter.

~~47.~~7. The acoustic wave device assembly of claim ~~4~~1 further comprising a via extending through the first die.

~~48.~~8. The acoustic wave device assembly of claim ~~4~~1 further comprising a wire bond extending from the second die.

~~49.~~9. The acoustic wave device assembly of claim ~~4~~1 wherein the first die is electrically isolated from the second die.

~~50.~~10. ~~The~~ An acoustic wave device assembly ~~of claim 41 further~~ comprising:

a first die including a first acoustic wave device configured to generate a boundary acoustic wave, the first acoustic wave device including a piezoelectric

layer, an interdigital transducer electrode on the piezoelectric layer, and high acoustic velocity layers on opposing sides of the piezoelectric layer, the high acoustic velocity layers each having an acoustic velocity that is greater than a velocity of the boundary acoustic wave;

a second die stacked with the first die, the second die including a second acoustic wave device configured to generate a second boundary acoustic wave; and

an air gap between the first die and the second die.

~~51. The acoustic wave device assembly of claim 41 further comprising a dielectric material disposed between the first die and the second die.~~

~~52.~~11. The acoustic wave device assembly of claim ~~4~~1 further comprising ~~a dielectric material and~~ a metal shield disposed between the first die and the second die.

~~53.~~12. The acoustic wave device assembly of claim ~~4~~1 wherein the second acoustic wave device includes a second piezoelectric layer, a second interdigital transducer electrode on the second piezoelectric layer, and second high acoustic velocity layers on opposing sides of the second piezoelectric ~~substrate~~layer, the second high acoustic velocity layers each having an acoustic velocity that is greater than a velocity of the second boundary acoustic wave.

~~54.~~13. A radio frequency module with acoustic wave filters, the radio frequency module comprising:

a first acoustic wave filter configured to filter a first radio frequency signal, the first acoustic wave filter including a first acoustic wave device on a first die and configured to generate a boundary acoustic wave, the first acoustic wave device including a piezoelectric layer and high acoustic velocity layers on opposing sides of the piezoelectric layer, the high acoustic velocity layers each having an acoustic velocity that is greater than a velocity of the boundary acoustic wave;

a second acoustic wave filter configured to filter a second radio frequency signal, the second acoustic wave filter including a second acoustic wave device on a

second die and configured to generate a second boundary acoustic wave, the second die being stacked with the first die; and

a package enclosing the first acoustic wave filter and the second acoustic wave filter, the radio frequency module having a thickness that is less than 300 micrometers.

~~55.~~14. The radio frequency module of claim ~~54~~13 ~~wherein a thickness of the radio frequency module is less than 300 micrometers~~further comprising at least one of an air gap or a dielectric layer disposed between the first die and the second die.

~~56.~~15. The radio frequency module of claim ~~54~~ 13 wherein a duplexer includes the first acoustic wave filter and the second acoustic wave filter.

16. The radio frequency module of claim ~~54~~ 13 further comprising a radio frequency switch coupled to the first acoustic wave filter and the second acoustic wave filter, the radio frequency switch being enclosed within the package.

17. The acoustic wave device assembly of claim 10 further comprising a third die stacked with the first die and the second die, the third die including a third acoustic wave device configured to generate a third boundary acoustic wave.

18. The acoustic wave device assembly of claim 10 wherein the first acoustic wave device further includes a temperature compensation layer disposed between the piezoelectric layer and a first high acoustic velocity layer of the high acoustic velocity layers.

19. The acoustic wave device assembly of claim 10 wherein a first high acoustic velocity layer of the high acoustic velocity layers is a silicon layer.

20. The acoustic wave device assembly of claim 10 wherein the first acoustic wave device is included in a first acoustic wave filter and the second acoustic wave device is included in a second acoustic wave filter.

~~57.~~21. The acoustic wave device assembly of claim 10 wherein the second acoustic wave device includes a second piezoelectric layer, a second interdigital transducer electrode on the second piezoelectric layer, and second high acoustic velocity layers on opposing sides of the second piezoelectric layer, the second high acoustic velocity layers each having an acoustic velocity that is greater than a velocity of the second boundary acoustic wave.

~~58. A wireless communication device comprising:~~

~~an antenna; and~~

~~acoustic wave filters in communication with the antenna, the acoustic wave filters being configured to filter radio frequency signals, the acoustic wave filters including a first die stacked with a second die, the first die including a first acoustic wave device configured to generate a boundary acoustic wave and including a piezoelectric layer disposed between two high acoustic velocity layers having acoustic velocities that are higher than a velocity of the boundary acoustic wave.~~

~~59. The wireless communication device of claim 58 further comprising a transceiver in communication with the acoustic wave filters.~~

~~60. The wireless communication device of claim 58 further comprising a radio frequency switch, the acoustic wave filters arranged as a multiplexer that is coupled to the radio frequency switch.~~