SUMMARY

[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 of this disclosure refers to a bulk acoustic wave device with a multi-gradient raised frame. The bulk acoustic wave device includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced. The multi-gradient raised frame structure is continuously tapered on opposing sides that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region. The bulk acoustic wave device is configured to generate a bulk acoustic wave.

[0008] The multi-gradient raised frame structure can surround the main acoustically active region of the bulk acoustic wave device in plan view. The multi-gradient raised frame structure can have a non-gradient portion between two gradient portions. The multi-gradient raised frame structure can consists essentially of gradient portions.

[0009] The multi-gradient raised frame structure can include a plurality of raised frame layers. The plurality of raised frame layers can include a first raised frame layer and a second raised frame layer. The second raised frame layer can extend beyond the first raised frame layer on the opposing sides. The first raised frame layer can have a lower acoustic impedance than the piezoelectric layer and/or the second raised frame layer. The first raised frame layer can be an oxide layer, and the second raised frame layer can be metallic. The first raised frame layer can be a silicon dioxide layer, and the second raised frame layer can be metallic. The first raised frame layer can be positioned between the first and second electrodes. The second electrode can be positioned between the first and second raised frame layers in some instances. The second raised frame layer can have a first taper angle on a first side and a second taper angle on a second side, in which and the first and second taper angles are in a range from 5 degrees to 45 degrees.

[0010] The multi-gradient raised frame structure can be a convex structure relative to the piezoelectric layer.

[0011] The bulk acoustic wave device can be a film bulk acoustic resonator.

[0012] Another aspect of this disclosure refers to an acoustic wave filter with a multi-gradient raised frame bulk acoustic wave device. The acoustic wave filter includes a bulk acoustic wave device and at least one additional acoustic wave device that are together arranged to filter a radio frequency signal. The bulk acoustic wave device includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced. The multi-gradient raised frame structure is continuously tapered on opposing sides that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region.

[0013] The least one additional acoustic wave device can include a second bulk acoustic wave device that includes a second multi-gradient raised frame structure that is tapered on opposing sides.

[0014] The multi-gradient raised frame structure can include a first raised frame layer and a second raised frame layer. The first raised frame layer can include an oxide, and the second raised frame layer can be metallic. The second raised frame layer can extend beyond the first raised frame layer on the opposing sides.

[0015] Another aspect of this disclosure refers to a wireless communication device that comprises an acoustic wave filter and an antenna operatively coupled to the acoustic wave filter. The acoustic wave filter includes a bulk acoustic wave device. The bulk acoustic wave device includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced. The multi-gradient raised frame structure is continuously tapered on opposing sides that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region.

[0016] The wireless communication device can be a mobile phone. The acoustic wave filter can be included in a multiplexer.

[0017] An example of this disclosure includes a bulk acoustic wave device with a multi-gradient raised frame. The bulk acoustic wave device comprises a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure. The multi-gradient raised frame structure includes a first raised frame layer and a second raised frame layer. The second raised frame layer extends beyond the first raised frame layer. The second raised frame layer

is tapered on opposing sides. The bulk acoustic wave device is configured to generate a bulk acoustic wave.

[0018] The second raised frame layer can extend beyond the first raised frame layer on the opposing sides, where the opposing sides include a first side toward a main acoustically active region of the bulk acoustic wave device and a second side away from the main acoustically active region.

[0019] The first raised frame layer can have a lower acoustic impedance than the piezoelectric layer. The first raised frame layer can include an oxide, and the second raised frame layer can include a metal. The second raised frame layer can include one or more of ruthenium, molybdenum, tungsten, platinum, or iridium.

[0020] The first raised frame layer can include a metal. The first raised frame layer can include a polymer.

[0021] The multi-gradient raised frame structure can have a non-gradient portion between two gradient portions. The multi-gradient raised frame structure can consist essentially of gradient portions.

[0022] The first raised frame layer can be positioned between the first electrode and the second electrode.

[0023] The second electrode can be positioned between the second raised frame layer and the first raised frame layer. The first raised frame layer can also be positioned between the piezoelectric layer and the second electrode.

[0024] The second raised frame layer can have a first taper angle on a first side and a second taper angle on a second side, and the first and second taper angles can each be greater than 5 degrees and less than 45 degrees.

[0025] The second raised frame layer can be a convex structure relative to a surface of the piezoelectric layer.

[0026] The multi-gradient raised frame structure can surround a main acoustically active region of the bulk acoustic wave device in plan view.

[0027] The bulk acoustic wave device can be a film bulk acoustic resonator.

[0028] Another example of this disclosure includes an acoustic wave filter that comprises a bulk acoustic wave device and at least one additional acoustic wave device together arranged to filter a radio frequency signal. The bulk acoustic wave device includes a first electrode, a

second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure including a first raised frame layer and a second raised frame layer. The second raised frame layer extends beyond the first raised frame layer. The second raised frame layer is tapered on opposing sides.

[0029] The at least one additional acoustic wave device can include a second bulk acoustic wave device that includes a second multi-gradient raised frame structure that is tapered on opposing sides.

[0030] Another example of this disclosure includes a packaged radio frequency module that comprises an acoustic wave filter configured to filter a radio frequency signal, a radio frequency circuit element, and a package structure enclosing the acoustic wave filter and the radio frequency circuit element. The acoustic wave filter includes a bulk acoustic wave device. The bulk acoustic wave device includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure including a first raised frame layer and a second raised frame layer. The second raised frame layer extends beyond the first raised frame layer. The second raised frame layer is tapered on opposing sides.

[0031] The radio frequency circuit element can be a radio frequency switch. The radio frequency circuit element can be a radio frequency amplifier.

[0032] Another example of this disclosure includes a bulk acoustic wave device that includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-layer raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced. The multi-layer raised frame structure includes a first raised frame layer embedded in the piezoelectric layer and a second raised frame layer. The first raised frame layer has a lower acoustic impedance than the piezoelectric layer. The second raised frame layer at least partly overlaps with the first raised frame layer in a raised frame region of the bulk acoustic wave device. The bulk acoustic wave device is configured to generate a bulk acoustic wave.

[0033] The second raised frame layer can be embedded in the piezoelectric layer.

[0034] The first raised frame layer can include an oxide, and the second raised frame layer can include a metal. The first raised frame layer can be a silicon dioxide layer,

and the second raised frame layer can be metallic. The second raised frame layer can be embedded in the piezoelectric layer.

[0035] The multi-layer raised frame structure can be a multi-gradient raised frame structure. The second raised frame layer can extend beyond the first raised frame layer on opposing sides of the multi-layer raised frame structure. The multi-gradient raised frame structure can have a non-gradient portion between two gradient portions. The second raised frame layer can have a first taper angle on a first side and a second taper angle on a second side, and the first and second taper angles can each be greater than 5 degrees and less than 45 degrees.

[0036] The multi-layer raised frame structure can surround the main acoustically active region of the bulk acoustic wave device in plan view.

[0037] The bulk acoustic wave device can be a film bulk acoustic resonator.

[0038] Another example of this disclosure includes an acoustic wave filter comprising that includes a bulk acoustic wave device and the at least one additional acoustic wave device together arranged to filter a radio frequency signal. The bulk acoustic wave device includes a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-layer raised frame structure including a first raised frame layer and a second raised frame layer. The first raised frame layer is embedded in the piezoelectric layer and has a lower acoustic impedance than the piezoelectric layer. The second raised frame layer at least partly overlaps with the first raised frame layer.

[0039] The at least one additional acoustic wave device can include a second bulk acoustic wave device that includes a raised frame layer embedded in a piezoelectric layer of the second bulk acoustic wave device.

[0040] The multi-layer raised frame structure can be a multi-gradient raised frame structure. The second raised frame layer can have a first taper angle on a first side and a second taper angle on a second side, and the first and second taper angles can each be greater than 5 degrees and less than 45 degrees. The first raised frame layer can be an oxide, and the second raised frame layer can be metallic. The first raised frame layer can be a silicon dioxide layer.

[0041] Another example of this disclosure includes a packaged radio frequency module that includes an acoustic wave filter, a radio frequency circuit element, and a package

WHAT IS CLAIMED IS:

1. A bulk acoustic wave device with a multi-gradient raised frame, the bulk acoustic wave device comprising:

a first electrode;

a second electrode;

a piezoelectric layer positioned between the first electrode and the second electrode; and

a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced, the multi-gradient raised frame structure being continuously tapered on opposing sides that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region, and the bulk acoustic wave device being configured to generate a bulk acoustic wave.

2. The bulk acoustic wave device of claim 1 wherein the multi-gradient raised frame structure surrounds the main acoustically active region of the bulk acoustic wave device in plan view.

3. The bulk acoustic wave device of claim 1 wherein the multi-gradient raised frame structure has a non-gradient portion between two gradient portions.

4. The bulk acoustic wave device of claim 1 wherein the multi-gradient raised frame structure consists essentially of gradient portions.

5. The bulk acoustic wave device of claim 1 wherein the bulk acoustic wave device is a film bulk acoustic resonator.

6. The bulk acoustic wave device of claim 1 wherein the multi-gradient raised frame structure includes a plurality of raised frame layers.

7. The bulk acoustic wave device of claim 6 wherein the plurality of raised frame layers include a first raised frame layer and a second raised frame layer, and the second raised frame layer extends beyond the first raised frame layer on the opposing sides.

8. The bulk acoustic wave device of claim 7 wherein the first raised frame layer has a lower acoustic impedance than at least one of the piezoelectric layer or the second raised frame layer.

9. The bulk acoustic wave device of claim 7 wherein the first raised frame layer is an oxide layer, and the second raised frame layer is metallic.

10. The bulk acoustic wave device of claim 7 wherein the first raised frame layer is a silicon dioxide layer, and the second raised frame layer is metallic.

11. The bulk acoustic wave device of claim 7 wherein the first raised frame layer is positioned between the first and second electrodes.

12. The bulk acoustic wave device of claim 11 wherein the second electrode is positioned between the first and second raised frame layers.

13. The bulk acoustic wave device of claim 7 wherein the second raised frame layer has a first taper angle on a first side and a second taper angle on a second side, and the first and second taper angles are in a range from 5 degrees to 45 degrees.

14. The bulk acoustic wave device of claim 1 wherein the multi-gradient raised frame structure is a convex structure relative to the piezoelectric layer.

15. An acoustic wave filter with a multi-gradient raised frame bulk acoustic wave device, the acoustic wave filter comprising:

a bulk acoustic wave device including a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced, the multi-gradient raised frame structure being continuously tapered on opposing sides that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region; and

at least one additional acoustic wave device, the bulk acoustic wave device and the at least one additional acoustic wave device together arranged to filter a radio frequency signal.

16. The acoustic wave filter of claim 15 wherein at least one additional acoustic wave device includes a second bulk acoustic wave device that includes a second multi-gradient raised frame structure that is tapered on opposing sides.

17. The acoustic wave filter of claim 15 wherein the multi-gradient raised frame structure includes a first raised frame layer and a second raised frame layer, the first raised frame layer includes an oxide, the second raised frame layer is metallic, and the second raised frame layer extends beyond the first raised frame layer on the opposing sides.

18. A wireless communication device comprising:

an acoustic wave filter including a bulk acoustic wave device, the bulk acoustic wave device including a first electrode, a second electrode, a piezoelectric layer positioned between the first electrode and the second electrode, and a multi-gradient raised frame structure configured to cause lateral energy leakage from a main acoustically active region of the bulk acoustic wave device to be reduced, the multi-gradient raised frame structure being continuously tapered on opposing sides

that both overlap with the first electrode and the second electrode, a first side of the opposing sides is between a second side of the opposing sides and the main acoustically active region; and

an antenna operatively coupled to the acoustic wave filter.

19. The wireless communication device of claim 18 wherein the wireless communication device is a mobile phone.

20. The wireless communication device of claim 18 wherein the acoustic wave filter is included in a multiplexer.