## 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 of this disclosure is 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 tapered on opposing sides. 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 is 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 tapered on opposing sides.

**[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 refer to~~is~~ a wireless communication device that comprises ~~includes~~ 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 tapered on opposing sides.

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

**[0017]** Another aspect of this disclosure is a bulk acoustic wave device with a multi-gradient raised frame. The bulk acoustic wave device comprises~~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. 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 aspect of this disclosure refer to~~is~~ an acoustic wave filter that comprises ~~includes~~ 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 aspect of this disclosure refer to~~is~~ a packaged radio frequency module that comprises ~~includes~~ 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 aspect of this disclosure is 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 aspect of this disclosure is 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 aspect of this disclosure is a packaged radio frequency module that includes an acoustic wave filter, 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-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.

**[0042]** The radio frequency circuit element can be a radio frequency switch. The radio frequency circuit element can be a radio frequency amplifier.

**[0043]** For purposes of summarizing the disclosure, certain aspects, advantages and novel features of the innovations have been described herein. It is to be understood that not necessarily all such advantages may be achieved in accordance with any particular embodiment. Thus, the innovations may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0044]** Embodiments of this disclosure will now be described, by way of non-limiting example, with reference to the accompanying drawings.

**[0045]** Figure 1 is a schematic cross-sectional view of a bulk acoustic wave (BAW) device with a dual gradient raised frame structure according to an embodiment.

**[0046]** Figure 2A is a plan view of an example BAW device with a frame region surrounding a main acoustically active region. Figure 2B is a plan view of another BAW device with a frame region surrounding a main acoustically active region.

**[0047]** Figure 3A is a cross sectional view of a BAW device with a dual gradient raised frame structure. Figure 3B shows simulation results for the BAW device of Figure 3A.