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] In accordance with one aspect of the disclosure, a bulk acoustic wave device can include a first electrode, a second electrode, and a piezoelectric layer between the first electrode and the second electrode. The device can have an active region where the piezoelectric layer overlaps the first electrode and the second electrode. The active region can include a middle area. The device can have a raised frame structure outside the middle area of the active region. The raised frame structure can include a gap between the first electrode and the second electrode so that at least a portion of the raised frame structure is a suspended frame that is suspended over the gap.

[0008] The piezoelectric layer can be over the first electrode, the second electrode can be over the piezoelectric layer, and the gap can be between the first electrode and the piezoelectric layer. The piezoelectric layer can be over the first electrode, the second electrode can be over the piezoelectric layer, and the gap can be between the second electrode and the piezoelectric layer. The raised frame structure can include an inner raised frame portion outside the middle area and inside the suspended frame. The suspended frame can have a height that is taller than a height of the inner raised frame portion. The raised frame structure can include a raised frame layer that extends over at least a portion of the gap. The raised frame layer can extend inward of the gap to form at least a portion of the inner raised frame portion of the raised frame structure. The raised frame layer can have a lower acoustic impedance than at least one of the first electrode, the second electrode, and the piezoelectric layer. The bulk acoustic wave device can further include a passivation layer over the first electrode, the second electrode, the piezoelectric layer, and the raised frame structure. A recessed frame region can be between the raised frame structure and the middle area, and the passivation layer can be thinner at the recessed frame region than at the middle area. The bulk acoustic wave device can include a conducive layer disposed over a portion of the passivation layer, and a portion of the conductive layer can extend into an opening in the passivation layer to electrically contact the second electrode. The opening in the passivation layer can be directly over the gap. A portion of the gap can extends laterally

piezoelectric layer. The bulk acoustic wave device can include an acoustic Bragg reflector, and the first electrode can be between the acoustic Bragg reflector and the piezoelectric layer.

[0011] In accordance with one example of the disclosure a filter that includes one or more of the bulk acoustic wave devices disclosed herein. The filter can be at least one of a band pass filter, a band stop filter, a ladder filter, and a lattice filter. A filter that includes one or more bulk acoustic wave devices disclosed herein can form part of at least one of a diplexer, a duplexer, a multiplexer, and a switching multiplexer. A radio frequency module can include an acoustic wave die including at least one filter that includes one or more of the bulk acoustic wave devices disclosed herein, and a radio frequency circuit element coupled to the acoustic wave die. The acoustic wave die and the radio frequency circuit element can be enclosed within a common module package. A wireless communication device can include an acoustic wave filter including one or more of the bulk acoustic wave devices disclosed herein, an antenna operatively coupled to the acoustic wave filter, a radio frequency amplifier operatively coupled to the acoustic wave filter and configured to amplify a radio frequency signal, and a transceiver in communication with the radio frequency amplifier. The wireless communication device can include a baseband processor in communication with the transceiver. The acoustic wave filter can be included in a radio frequency front end. The wireless communication device can be a user equipment.

[0012] In accordance with one aspect of the disclosure, a bulk acoustic wave device can include a first electrode, a second electrode, a piezoelectric layer between the first electrode and the second electrode, with a portion of the first electrode extending laterally past an end of the piezoelectric layer, a portion of the second electrode extending laterally past the end of the piezoelectric layer, and a gap disposed between the portion of the first electrode and the portion of the second electrode.

[0013] The bulk acoustic wave device can include a suspended frame structure that includes a portion of the gap. The bulk acoustic wave device can include a raised frame structure that includes a suspended frame portion that is suspended over a portion of the gap and an inner raised frame portion that is laterally inward of the suspended frame portion. The raised frame structure can include a raised frame layer between the first electrode and the second electrode. The inner raised frame portion can include a first portion of the raised frame layer that is not over the gap, and the suspended frame portion can include a second

[0016] A filter can include one or more of the bulk acoustic wave devices disclosed herein. The filter can be at least one of a band pass filter, a band stop filter, a ladder filter, and a lattice filter. A filter that includes one or more bulk acoustic wave devices disclosed herein can form part of at least one of a diplexer, a duplexer, a multiplexer, and a switching multiplexer. A radio frequency module can include an acoustic wave die with at least one filter that has one or more of the bulk acoustic wave devices disclosed herein, and a radio frequency circuit element coupled to the acoustic wave die. The acoustic wave die and the radio frequency circuit element can be enclosed within a common module package. A wireless communication device can include an acoustic wave filter including one or more of the bulk acoustic wave devices disclosed herein, an antenna operatively coupled to the acoustic wave filter, a radio frequency amplifier operatively coupled to the acoustic wave filter and configured to amplify a radio frequency signal, and a transceiver in communication with the radio frequency amplifier. The wireless communication device can include a baseband processor in communication with the transceiver. The acoustic wave filter can be included in a radio frequency front end. The wireless communication device can be user equipment.

[0017] In accordance with one example of the disclosure, a method of making a bulk acoustic wave device can include forming a first electrode over a substrate, forming a piezoelectric layer over the first electrode, forming a sacrificial layer over the piezoelectric layer, forming a second electrode over the sacrificial layer, and removing the sacrificial layer to produce a gap between the first electrode and the second electrode, the gap elevating a portion of the second electrode to provide a suspended frame.

[0018] The method can include forming an inner raised frame portion disposed laterally inward of the suspended frame. The suspended frame can be formed with a height that is taller than a height of the inner raised frame. The method can include forming a raised frame layer with a first portion over the piezoelectric layer and not extending over the sacrificial layer and a second portion that extends over the sacrificial layer. The method can include forming a first raised frame layer over the piezoelectric layer, with the second electrode formed over the first raised frame layer. The method can include forming a second raised frame layer over the second electrode. The first raised frame layer can have a lower acoustic impedance than the second raised frame layer. The method can include forming a

passivation layer over the second electrode. The method can include forming an opening through the passivation layer and forming a conducive layer over a portion of the passivation layer with a portion of the conductive layer extending into the opening in the passivation layer to electrically contact the second electrode. The opening through the passivation layer can be disposed directly over gap. A portion of the sacrificial layer can be formed extending laterally outward past an end of the piezoelectric layer, and removal of the sacrificial layer can form the gap extending laterally outward past the end of the piezoelectric layer. The method can include forming a cavity sacrificial layer over a portion of the substrate, with the first electrode formed over the cavity sacrificial layer, and the method can include removing the cavity sacrificial layer to produce a cavity between the substrate and the first electrode. The cavity sacrificial layer can be removed to form the cavity at the same time that the sacrificial layer is removed to form the gap.

[0019] In accordance with one example of the disclosure, a method of making a bulk acoustic wave device can include forming a first electrode over a substrate, forming a piezoelectric layer over the first electrode, with a portion of the first electrode extending past an end of the piezoelectric layer, forming a sacrificial layer over a portion of the piezoelectric layer and over the portion of the lower electrode, forming a second electrode over the sacrificial layer, with a portion of the second electrode extending past the end of the piezoelectric layer, and removing the sacrificial layer to produce a gap between the portion of the first electrode and the portion of the second electrode.

[0020] The gap can elevate a portion of the second electrode to provide a suspended frame. The method can include forming an inner raised frame portion disposed laterally inward of the suspended frame. The suspended frame can be formed with a height that is taller than a height of the inner raised frame. The method can include forming a raised frame layer with a first portion over the piezoelectric layer and not extending over the sacrificial layer and a second portion that extends over the sacrificial layer. The method can include forming a first raised frame layer over the piezoelectric layer, with the second electrode formed over the first raised frame layer, and the method can include forming a second raised frame layer over the second electrode. The first raised frame layer can have a lower acoustic impedance than the second raised frame layer. The method can include forming a passivation layer over the second electrode. The method can include forming an