

DEVICE FOR CONTROLLING AN ION, METHOD FOR FORMING THE SAME, AND  
METHOD FOR CONTROLLING AN ION

**Cross-Reference To Related Application**

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[0001] This application claims the benefit of priority of Singapore patent application No. 10202110905T, filed 30 September 2021, the content of it being hereby incorporated by reference in its entirety for all purposes.

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**Technical Field**

[0002] Various embodiments relate to a device for controlling an ion, a method for forming a device for controlling an ion, and a method for controlling an ion.

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**Background**

[0003] Quantum computing demonstrates superior capability in solving problems which are intractable for its classical computing counterparts since quantum bits (i.e., qubits) can represent the coherent superposition state of basis states  $|0\rangle$  and  $|1\rangle$ . As a promising physical implementation for qubits, trapped ions feature favourable properties (e.g., long coherence time and high fidelity) for quantum operations. In addition, the development of surface electrode ion trap (linear trap) has drawn significant attention in the quantum computing community due to compatibility with microfabrication techniques, enabling a flexible, repeatable and fundamentally scalable design of ion trap. Despite extensive advances that have been made in terms of technical challenges elimination (e.g., on-chip optical/electrical control) in current surface electrode ion trap devices, further improvement at the fundamental level is required for large scale implementation. Limited by the relatively low trapping depth, the ion-electrode distance (trapping height,  $d$ ) in surface electrode ion trap is kept small. Since anomalous ion-motional heating approximately scales as  $d^{-4}$ , a small  $d$  will force ions to suffer from extremely high anomalous motional heating and consequently low fidelity for quantum operations. On the other hand, for large-scale ion trap (noisy intermediate-scale quantum, 50 to 100 ions) which

will feature large dimensions and planar instead of a linear layout, the laser beams focusing on the ions with a tight ion-electrode distance while not interfering with the trap surface become remarkably challenging. In reference to these challenges, the ability for ion-electrode distance adjustment for certain ions in a large-scale ion trap is highly in demand.

- 5   **[0004]** Generally, ions are radially confined at the RF (radio frequency) null of dynamic RF field in a surface electrode ion trap. Though the trapping height adjustment may be facilitated by DC (direct current) potentials control, the offset between the ions and the RF null will result in intensified micromotion. The existing in-situ approach (no excess micromotion) for trapping height adjustment is mainly dependent on the point trap having a circular electrode geometry.
- 10   By applying RF potentials with different amplitudes on two concentric circular electrodes, the RF null height can be moved accordingly. However, the circular electrodes hamper its integration with linear trap that has a rectangular geometry, limiting the application in large-scale quantum computing.

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### **Summary**

**[0005]** The invention is defined in the independent claims. Further embodiments of the invention are defined in the dependent claims.

- 20   **[0006]** According to an embodiment, a device for controlling an ion is provided. The device may include a point trap electrode arrangement, and a linear trap electrode arrangement, wherein the device is operable in a first mode, a second mode, and a combination thereof, wherein, in the first mode, the point trap electrode arrangement is configured to generate a first radio frequency (RF) field having a point RF null to trap the ion at the point RF null above a surface of the device, and wherein a distance of the point RF null to the surface is variable in
- 25   response to a change in a potential of an RF signal applied to the point trap electrode arrangement, and wherein, in the second mode, the linear trap electrode arrangement is configured to generate a second RF field having a linear RF null to trap the ion at the linear RF null above the surface, and wherein the ion is movable along the linear RF null in response to a change in a potential of at least one direct current (DC) signal applied to the linear trap
- 30   electrode arrangement.

[0007] According to an embodiment, a method for forming a device for controlling an ion is provided. The method may include forming a point trap electrode arrangement on a support structure, and forming a linear trap electrode arrangement on the support structure, wherein the device is operable in a first mode, a second mode, and a combination thereof, wherein, in the first mode, the point trap electrode arrangement is configured to generate a first radio frequency (RF) field having a point RF null to trap the ion at the point RF null above a surface of the device, and wherein a distance of the point RF null to the surface is variable in response to a change in a potential of an RF signal applied to the point trap electrode arrangement, and wherein, in the second mode, the linear trap electrode arrangement is configured to generate a second RF field having a linear RF null to trap the ion at the linear RF null above the surface, and wherein the ion is movable along the linear RF null in response to a change in a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement.

[0008] According to an embodiment, a method for controlling an ion is provided. The method may include generating, via a linear trap electrode arrangement of a device for controlling the ion, a radio frequency (RF) field having a linear RF null to trap the ion at the linear RF null above a surface of the device, adjusting a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement to move the ion along the linear RF null between the linear trap electrode arrangement and a point trap electrode arrangement of the device, generating, via the point trap electrode arrangement, another RF field having a point RF null to trap the ion at the point RF null above the surface, and adjusting a potential of an RF signal applied to the point trap electrode arrangement to vary a distance of the point RF null to the surface.

### **Brief Description of the Drawings**

[0009] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0010] FIG. 1A shows a schematic perspective view of a device for controlling an ion, according to various embodiments.

[0011] FIG. 1B shows a flow chart illustrating a method for forming a device for controlling an ion, according to various embodiments.

[0012] FIG. 1C shows a flow chart illustrating a method for controlling an ion, according to various embodiments.

5 [0013] FIGS. 2A to 2C show schematic top views of geometry development of an integrated trap of various embodiments.

[0014] FIGS. 3A to 3D show the device of FIG. 2C having an integrated ion trap operating in a point trap mode according to various embodiments.

10 [0015] FIGS. 4A to 4D show the device of FIG. 2C having an integrated ion trap operating in a linear trap mode according to various embodiments.

[0016] FIGS. 5A to 5D show the device of FIG. 2C having an integrated ion trap operating in a combination mode according to various embodiments.

[0017] FIGS. 6A to 6M show, as cross-sectional views, various processing stages of a fabrication process for an integrated ion trap, according to various embodiments.

15 [0018] FIGS. 7A and 7B schematically illustrate scaling up of the integrated ion trap.

### **Detailed Description**

20 [0019] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined  
25 with one or more other embodiments to form new embodiments.

[0020] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

30 [0021] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments,

even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

**[0022]** In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

**[0023]** In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

**[0024]** As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

**[0025]** Various embodiments may provide a device for trapping ions having a linear trap arrangement and a point trap arrangement, wherein the point trap arrangement may be integrated with the linear trap arrangement. The device may be configured to operate in a linear trap mode, a point trap mode, and a combination mode of the linear trap mode and the point trap mode. The point trap arrangement may include a plurality of point traps integrated with the linear trap arrangement. Each point trap may have a square geometry which facilitates integration with the linear trap arrangement.

**[0026]** Various embodiments may relate to a square point trap and the integration with a linear trap for large-scale quantum computing. A linear trap is a trap geometry, indicating a specific electrode configuration. For a linear trap, the electrode dimension in one direction is significantly larger than the other two dimensions, which is more friendly for laser beams. If the surface geometry extends in two dimensions simultaneously, the access for laser beams may be compressed. The term “linear” for a linear trap also indicates an ion shuttling path in a linear direction, e.g, in an axial direction as described herein below.

**[0027]** To resolve or address the above-mentioned issues related to the prior art, various embodiments may provide a point trap that may have a square geometry which may be integrated with a linear trap. A two-dimensional ion shuttling path may be built: an ion movement in an axial direction that may be supported by a linear trap with DC potentials tuning, whereas the trapping height may be in-situ adjusted by RF amplitudes in the point trap. When the point trap is not in operation, the required or corresponding electrodes of the point trap may be seamlessly combined with neighbouring electrodes and together work as an extended linear trap without or with minimal performance degradation. Similarly, when the

point trap is in operation, the other sections of the linear trap may work as normal except for leaving a small buffer region that is close to the point trap.

[0028] Various embodiments may provide a design of point trap with a square geometry which may be seamlessly integrated with a linear surface-electrode ion trap. This integration may allow for an ion shuttling in two dimensions, in which shuttling parallel to the surface (in axial direction) and perpendicular to the surface may respectively be enabled by tuning the DC potentials of the linear trap and the RF signal amplitudes of the point trap.

[0029] As a non-limiting example, ion shuttling may be able to transport quantum states between nodes of a larger system, which may be required for large scale quantum computing.

Two-dimensional shuttling may generally enable a higher flexibility for information transport as well as a large system design. Different from the linear trap that may have a nominal and constant trapping height of about 75  $\mu\text{m}$ , the point trap may be able to continually or continuously adjust the trapping height from about 20  $\mu\text{m}$  to about 120  $\mu\text{m}$  based on the modelling result. Since height adjustment may be realised by in-situ moving the RF null in the point trap, the undesired micromotion may be avoided, or at least minimised. In various embodiments, with the introduction of TSV (through-silicon via) and interposer, the integrated ion trap may be scaled up by aligning multiple individual traps together. This design enriches the toolbox for large-scale quantum computing. Also of interests may be mass ion addressing where a high numerical aperture may be required, and heating rate reduction for certain or selected ions.

[0030] The techniques disclosed herein may be of interest for mass ion addressing and heating rate reduction for certain or selected ions in a large-scale ion trap. Meanwhile, a variety of experimental applications may also benefit from the disclosed techniques. For example, high-resolution trapping height adjustment may make the alignment between laser beams and ions more straightforward, for example, in the case where grating couplers are on-chip integrated. Also, the in-situ trapping height adjustment capability itself may facilitate anomalous heating study. Further, provided the ions at different point traps may be interconnected and entangled (e.g., through optical fibers), the scalability of the integrated point and liner trap of various embodiments may be further boosted.

[0031] In various embodiments, by setting the electrodes potential accordingly, the integrated trap of various embodiments may be able to perform the individual mode of a linear trap, the individual mode of a point trap, as well as a combination mode of the two.

[0032] Various embodiments may provide a design having geometry compatibility which may allow for sufficiently good performance and/or scaling up. For example, the point trap may have a square geometry, and/or may include one or more electrode segments of a square geometry.

[0033] Various embodiments may provide a design including three central electrodes having square segmentations, thus providing a physical appearance that may be easily visually recognised.

[0034] FIG. 1A shows a schematic perspective view of a device 100 for controlling an ion 106, according to various embodiments. The device 100 includes a point trap electrode arrangement 102, and a linear trap electrode arrangement 104, wherein the device 100 is operable in a first mode, a second mode, and a combination thereof, wherein, in the first mode, the point trap electrode arrangement 102 is configured to generate a first radio frequency (RF) field having a point RF null to trap the ion 106 at the point RF null above a surface 108 of the device 100, and wherein a distance of the point RF null to the surface 108 is variable in response to a change in a potential of an RF signal applied to the point trap electrode arrangement 102, and, wherein, in the second mode, the linear trap electrode arrangement 104 is configured to generate a second RF field having a linear RF null to trap the ion 106 at the linear RF null above the surface 108, and wherein the ion 106 is movable along the linear RF null in response to a change in a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement 104.

[0035] In other words, a device 100 for controlling or manipulating an ion 106 may be provided. The device 100 may include a point trap electrode arrangement 102, and a linear trap electrode arrangement 104. The point trap electrode arrangement 102 and/or the linear trap electrode arrangement 104 may be a surface electrode arrangement. The point trap electrode arrangement 102 and the linear trap electrode arrangement 104 may be arranged coaxially. The point trap electrode arrangement 102 and the linear trap electrode arrangement 104 may be integrated with one another. Part of the point trap electrode arrangement 102 may be in common with the linear trap electrode arrangement 104. In other words, the device 100 may

include one or more electrode segments that may be shared by the point trap electrode arrangement 102 and the linear trap electrode arrangement 104.

[0036] Non-limiting examples for the ion 106 may include Be<sup>+</sup> (beryllium), Mg<sup>+</sup> (magnesium), Ca<sup>+</sup> (calcium), Sr<sup>+</sup> (strontium), Cd<sup>+</sup> (cadmium), Ba<sup>+</sup> (barium), and Yb<sup>+</sup> (ytterbium). Simulation work and results as described herein are based on Sr<sup>+</sup>.

[0037] The device 100 may be operable or operated in three modes - a first mode, a second mode, and a combination of the first and second modes. At any one time, the device 100 may be operated in the first mode, the second mode, or a combination mode involving the first mode and the second mode.

[0038] In the first mode, the point trap electrode arrangement 102 may be configured to generate a first RF (trapping) field including a point RF null (e.g., a 1D point RF null, or a single RF null point) to trap the ion 106 at the point RF null above a surface 108 of the device 100 (e.g., above a surface of the point trap electrode arrangement 102). It should be appreciated, therefore, that, in the first mode, the device 100 may function in a point trap mode.

The point trap electrode arrangement 102 may act as or define a point trap.

[0039] The (perpendicular) distance (or height) of the point RF null to the surface 108 may be variable in response to a change in a potential (or amplitude) of an RF signal applied to the point trap electrode arrangement 102. As the ion 106 may be trapped at the point RF null, changing the distance of the point RF null to the surface 108 effectively changes the position or distance of the trapped ion 106 to the surface 108. This allows movement of the ion 106 by tuning the potential or amplitude of the RF signal. The point trap electrode arrangement 102 may be configured to generate the first RF field in response to the RF signal and another RF signal applied to the point trap electrode arrangement 102.

[0040] In various embodiments, the distance of the point RF null to the surface 108 may be varied between about 20  $\mu\text{m}$  and about 120  $\mu\text{m}$ , for example, between about 20  $\mu\text{m}$  and about 100  $\mu\text{m}$ , between about 20  $\mu\text{m}$  and about 80  $\mu\text{m}$ , between about 20  $\mu\text{m}$  and about 50  $\mu\text{m}$ , between about 50  $\mu\text{m}$  and about 120  $\mu\text{m}$ , between about 50  $\mu\text{m}$  and about 100  $\mu\text{m}$ , or between about 80  $\mu\text{m}$  and about 120  $\mu\text{m}$ .

[0041] In the second mode, the linear trap electrode arrangement 104 may be configured to generate a second RF (trapping) field including a linear RF null (e.g., a 2D linear RF null, or an (uniform) RF null line) to trap the ion 106 at the linear RF null above the surface 108

(e.g., above a surface of the linear trap electrode arrangement 104). It should be appreciated, therefore, that, in the second mode, the device 100 may function in a linear trap mode. The linear trap electrode arrangement 104 may act as or define a linear trap. The linear trap electrode arrangement 104 may be configured to generate the second RF field in response to an RF signal applied to the linear trap electrode arrangement 104, which may be a third RF signal or any one of the RF signals applied to the point trap electrode arrangement 102. The first RF field and the second RF field may be independent from each other.

**[0042]** The ion 106 may be trapped at the linear RF null at a constant or uniform distance to the surface 108. The ion 106 may be movable along the linear RF null in response to a change in a potential (or amplitude) of at least one DC signal applied to the linear trap electrode arrangement 104.

**[0043]** In the combination mode, the device 100 may function in the point trap mode and the linear trap mode.

**[0044]** In the context of various embodiments, an RF null refers to a pseudopotential minimum. An RF null may be created by carefully configured RF field. For a linear trap (enabled by or corresponding to the linear trap electrode arrangement 104), the RF null may be in the form of a (2D) linear RF null or a 2D RF null line, while for a point trap (enabled by or corresponding to the point trap electrode arrangement 102), the RF null may be in the form of a point RF null or a 1D RF null point. An ion may be trapped or held at an RF null as the pseudopotential at the RF null is lower than the surrounding.

**[0045]** As described above, the trapping height of the ion 106, or the distance of the point RF null to the surface 108, may be adjusted by varying the potential or amplitude of the RF signal applied to the point trap electrode arrangement 102, while the movement of the ion 106 along the linear RF null may be controlled by varying the potential or amplitude of the at least one DC signal applied to the linear trap electrode arrangement 104. In other words, the ion 106 may be movable along the linear RF null (e.g., in the horizontal or axial direction) by tuning the potential(s) of the at least one DC signal applied to the linear trap electrode arrangement 104, and/or movable along a height direction relative to the surface 108 (e.g., in the vertical or perpendicular direction) by tuning the potential of the RF signal applied to the point trap electrode arrangement 102. The movement of the ion 106 enabled in the first mode and the

movement of the ion 106 enabled in the second mode may be along directions perpendicular to one another.

[0046] When operating in the first mode alone, part of the linear trap electrode arrangement 104 may be set as ground or DC. When operating in the second mode alone, part of the point trap electrode arrangement 102 may be set as ground or DC.

[0047] In various embodiments, a plurality of ions may be trapped and controlled by the device 100. For example, a plurality of ions may be trapped and controlled by the device 100 at the linear RF null above the surface 108, and each ion may be movable along the linear RF null. It should be appreciated that a plurality of ions may be confined (or trapped) and shuttled (or moved) simultaneously by the device 100.

[0048] In various embodiments, the point trap electrode arrangement 102 may have a (overall) square geometry. This may facilitate integration or enhanced integration with the linear trap electrode arrangement 104. The point trap electrode arrangement 102 may include one or more electrode segments of a square or rectangular geometry.

[0049] In various embodiments, the linear trap electrode arrangement 104 may include a plurality of electrode segments of a square or rectangular geometry.

[0050] In various embodiments, the point trap electrode arrangement 102 may include a square electrode segment to which the RF signal may be applied to. The RF signal may be applied to a single square electrode segment. The square electrode segment may be a central square electrode segment.

[0051] The point trap electrode arrangement 102 may further include an electrode region at least substantially surrounding the square electrode segment, the square electrode segment and the electrode region being configured to co-operatively generate the first RF field. The first RF field may be generated in response to the RF signal being applied to the square electrode segment and another RF signal being applied to the electrode region. The RF signal and the other RF signal may be in phase. The RF signal and the other RF signal may be of different amplitudes. The electrode region may have a plurality of electrode segments at least substantially surrounding the square electrode segment. A respective electrode segment of the plurality of electrode segments of the electrode region may have a square geometry or a rectangular geometry.

**[0052]** In various embodiments, the square electrode segment and the electrode region may be arranged in a square geometry. In other words, the square electrode segment, in combination with the electrode region, as a whole, may be arranged in a square shape. Nevertheless, it should be appreciated that the square electrode segment and the electrode region may instead be arranged in a rectangular geometry.

**[0053]** In various embodiments, the linear trap electrode arrangement 104 may include two linear electrode portions arranged at least substantially parallel to one another, and the two linear electrode portions may be configured to co-operatively generate the second RF field. The two linear electrode portions may be arranged symmetrically to one another. The two linear electrode portions may be arranged spaced apart from each other. The electrode segments of the electrode region that may be arranged adjacent to the square electrode segment and in a direction along the longitudinal axes of the two linear electrode portions may be of a square geometry.

**[0054]** A longitudinal axis of the linear RF null may be at least substantially parallel to the longitudinal axes of the two linear electrode portions. The linear RF null may be generated in between the two linear electrode portions. This may mean that the ion 106 may be trapped above the surface 108 of the device 100 in between the two linear electrode portions. The point trap electrode arrangement 102 may be arranged in between the two linear electrode portions.

**[0055]** Each of the two linear electrode portions may include a plurality of linear electrode segments. Each linear electrode segment may have a dimension in one direction (e.g., length) that is significantly larger than the dimensions in the other two directions.

**[0056]** The two linear electrode portions may be configured to co-operatively generate the second RF field in response to an RF signal applied to the two linear electrode portions. The RF signal applied to the two linear electrode portions may be a third RF signal.

**[0057]** The linear trap electrode arrangement 104 may further include two side electrode portions to which the at least one DC signal may be to be applied to, the two linear electrode portions being arranged in between the two side electrode portions, and, for each of the two side electrode portions, the side electrode portion may include a plurality of (side) electrode segments having longitudinal axes that may be oriented in a direction different to longitudinal axes of the two linear electrode portions. The plurality of electrode segments of the two side electrode portions may be arranged at least substantially parallel to one another. The plurality of

electrode segments of the two side electrode portions may be DC electrode segments. The two side electrode portions may be DC side electrode portions.

[0058] The device 100 may further include a support structure (or substrate) to support the point trap electrode arrangement 102 and the linear trap electrode arrangement 104. The point trap electrode arrangement 102 and the linear trap electrode arrangement 104 may be formed on the support structure, e.g., on the surface of the support structure. A plurality of through vias may be formed (or defined) in (and through) the support structure. For a respective through via of the plurality of through vias, the respective through via includes an electrically conductive material electrically coupled to the point trap electrode arrangement 102 or the linear trap electrode arrangement 104. This means that an electrically conductive material may be received in or filled into each through via. In various embodiments, the support structure may include or may be a silicon (Si) substrate, and the plurality of through vias may include a plurality of through silicon vias (TSVs).

[0059] The device 100 may further include a redistribution layer (RDL) (e.g., as part of an interposer) electrically coupled to the plurality of through vias. The plurality of through vias and the RDL may help with signal routing for application of RF signal(s) and DC signal(s) to the point trap electrode arrangement 102 and the linear trap electrode arrangement 104.

[0060] The device 100 may further include a plurality of point trap electrode arrangements arranged coaxially, wherein, for each point trap electrode arrangement of the plurality of point trap electrode arrangements, the point trap electrode arrangement may be configured to, in the first mode, generate the first RF field having the point RF null to trap a respective ion at the point RF null above the surface 108, wherein the distance of the point RF null to the surface 108 may be variable in response to the change in the potential of the RF signal applied to the point trap electrode arrangement. Each point trap electrode arrangement may enable a respective ion to be trapped and controlled. In this way, a plurality of ions may be individually controlled by respective point trap electrode arrangements. Each point trap electrode arrangement of the plurality of point trap electrode arrangements may be as described in the context of the point trap electrode arrangement 102.

[0061] FIG. 1B shows a flow chart 120 illustrating a method for forming a device for controlling an ion, according to various embodiments.

[0062] At 122, a point trap electrode arrangement is formed on a support structure.

**[0063]** At 124, a linear trap electrode arrangement is formed on the support structure.

**[0064]** The device is operable in a first mode, a second mode, and a combination thereof. In the first mode, the point trap electrode arrangement is configured to generate a first radio frequency (RF) field having a point RF null to trap the ion at the point RF null above a surface of the device, wherein a distance of the point RF null to the surface is variable in response to a change in a potential of an RF signal applied to the point trap electrode arrangement. In the second mode, the linear trap electrode arrangement is configured to generate a second RF field having a linear RF null to trap the ion at the linear RF null above the surface, wherein the ion is movable along the linear RF null in response to a change in a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement.

**[0065]** At 122, a square electrode segment to which the RF signal may be applied to may be formed.

**[0066]** At 122, an electrode region at least substantially surrounding the square electrode segment may further be formed, the square electrode segment and the electrode region being configured to co-operatively generate the first RF field.

**[0067]** At 124, two linear electrode portions arranged at least substantially parallel to one another may be formed. The two linear electrode portions may be configured to co-operatively generate the second RF field.

**[0068]** At 124, two side electrode portions to which the at least one DC signal may be applied to may further be formed, where the two linear electrode portions may be arranged in between the two side electrode portions. For each of the two side electrode portions, a plurality of electrode segments may be formed, having longitudinal axes that may be oriented in a direction different to longitudinal axes of the two linear electrode portions.

**[0069]** In various embodiments of the method, a plurality of through vias may be formed in the support structure. For a respective through via of the plurality of through vias, the respective through via includes an electrically conductive material electrically coupled to the point trap electrode arrangement or the linear trap electrode arrangement.

**[0070]** A redistribution layer (RDL) electrically coupled to the plurality of through vias may further be formed.

**[0071]** In various embodiments of the method, a plurality of point trap electrode arrangements arranged coaxially may be formed. For each point trap electrode arrangement of the plurality of

point trap electrode arrangements, the point trap electrode arrangement may be configured to, in the first mode, generate the first RF field having the point RF null to trap a respective ion at the point RF null above the surface, wherein the distance of the point RF null to the surface may be variable in response to the change in the potential of the RF signal applied to the point trap electrode arrangement.

[0072] FIG. 1C shows a flow chart 150 illustrating a method for controlling an ion, according to various embodiments.

[0073] At 152, a radio frequency (RF) field may be generated via a linear trap electrode arrangement of a device for controlling the ion, the RF field having a linear RF null to trap the ion at the linear RF null above a surface of the device.

[0074] At 154, a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement may be adjusted to move the ion along the linear RF null between the linear trap electrode arrangement and a point trap electrode arrangement of the device. This may mean that the potential of the at least one DC signal may be adjusted to move the ion along the linear RF null from the linear trap electrode arrangement to the point trap electrode arrangement, and from the point trap electrode arrangement to the linear trap electrode arrangement.

[0075] At 156, another RF field may be generated via the point trap electrode arrangement, the other RF field having a point RF null to trap the ion at the point RF null above the surface.

[0076] At 158, a potential of an RF signal applied to the point trap electrode arrangement may be adjusted to vary a distance of the point RF null to the surface.

[0077] In various embodiments, at 158, the RF signal may be applied to a square electrode segment of the point trap electrode arrangement, where the potential of the RF signal may be adjusted.

[0078] While the methods described above are illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[0079] It should be appreciated that description in relation to the device 100, the method for forming a device for controlling an ion in the context of the flow chart 120, and the method for controlling an ion described in the context of the flow chart 150, may be applicable to one another.

5 [0080] Various embodiments or techniques will now be further described in detail.

[0081] FIGS. 2A to 2C show schematic top views of geometry development of an integrated (ion) trap 200c of various embodiments. FIG. 2A shows a schematic top view of a linear trap electrode arrangement 204a. The linear trap electrode arrangement 204a may include two linear electrode portions 210a, 211a sandwiching a central linear electrode portion 212a. The  
10 electrode portions 210a, 211a, 212a may make up the central electrodes 214a. The two linear electrode portions 210a, 211a may be at least substantially parallel to one another. The two linear electrode portions 210a, 211a may be positioned symmetrically to one another. The electrode portions 210a, 211a, 212a may be at least substantially parallel to each other. The linear trap electrode arrangement 204a may further include two side electrode portions 216a,  
15 217a sandwiching the central electrodes 214a. Using the side electrode portion 217a as a non-limiting example, each side electrode portion 216a, 217a may include a plurality of electrode segments (three electrode segments shown represented by 218a). The plurality of (side) electrode segments 218a may have longitudinal axes that may be oriented in a different direction (e.g., perpendicularly) to the longitudinal axes of the two linear electrode  
20 portions 210a, 211a. The vertical and horizontal black lines in FIG. 2A represent inter-electrode gaps. For the linear trap electrode arrangement 204a, ions (not shown) may be shuttled along the y direction by tuning DC potentials applied to the (horizontal) electrode segments 218a of the two side electrode portions 216a, 217a.

[0082] FIG. 2B shows a schematic top view of a point trap electrode arrangement 202b with a  
25 square geometry. The point trap electrode arrangement 202b may include a (central) square electrode segment 220b. The square electrode segment 220b may be at least substantially surrounded by an electrode region having electrode segments 222b, 224b, 226b, 228b. The electrode segments 222b, 224b may have a square geometry, while the electrode segments 226b, 228b may have a rectangular geometry. The electrode segments 220b, 222b,  
30 224b, 226b, 228b may together define a square geometry. There may be other electrode segments 229b, 230b, 231b, 232b at least substantially surrounding the square electrode

segment 220b and the electrode region. The vertical and horizontal black lines in FIG. 2B represent inter-electrode gaps, which may be about 2  $\mu\text{m}$ . For the point trap electrode arrangement 202b, ions that are trapped by the point trap electrode arrangement 202b may be shuttled along the z direction.

5 [0083] FIG. 2C shows a schematic top view of an integrated trap electrode arrangement 240c, illustrating the geometry after integration of the linear trap electrode arrangement 204a of FIG. 2A and the point trap electrode arrangement 202b of FIG. 2B to form a device (or ion trap) 200c for controlling one or more ions. The integrated trap electrode arrangement 240c of the device 200c includes a point trap electrode arrangement (indicated by dashed circle 202c) and a linear trap electrode arrangement 204c. The point trap electrode arrangement 202c may have a square geometry. The device 200c may be operable in a point trap mode, a linear trap mode and a combination mode of the point trap mode and the linear trap mode as will be described further below.

10 [0084] The integrated trap electrode arrangement 240c may include central electrodes 214c having two linear electrode portions 210c, 211c, and a central linear electrode portion 212c therebetween, similar to the linear trap electrode arrangement 204a. However, different from the linear trap electrode arrangement 204a, the electrode portions 210c, 211c, 212c may be incorporated with inter-electrode gaps (i.e., opening or space between neighboring electrodes), e.g., with a dimension of 2  $\mu\text{m}$ , and electrode segmentations, where different electrical signals may be applied. Using the linear electrode portion 211c as a non-limiting example, each electrode portion 210c, 211c, 212c may include a plurality of electrode segments 241c, 242c, 243c, 244c. The width of each of the electrode portions 210c, 211c, 212c may be set as about 80  $\mu\text{m}$ . The vertical and horizontal black lines in FIG. 2C represent inter-electrode gaps, which may be designed with a width of about 2  $\mu\text{m}$ .

25 [0085] The point trap electrode arrangement 202c may include a (central) square electrode segment 220c at least substantially surrounded by an electrode region of square and rectangular electrode segments similar to the point trap electrode arrangement 202b. The electrode region may include a pair of square electrode segments 222c, 224c sandwiching the square electrode segment 220c, and a pair of rectangular electrode segments 226c, 228c sandwiching the square electrode segment 220c. The electrode segments 220c, 222c, 224c, 226c, 228c may together, as a whole, define a square geometry, or may be arranged in a square geometry, to be integrated

with the linear trap electrode arrangement 204c. Nevertheless, it should be appreciated that the electrode segments 220c, 222c, 224c, 226c, 228c may, as a whole, define a rectangular geometry to be integrated with the linear trap electrode arrangement 204c.

[0086] The integrated trap electrode arrangement 240c may further include two side electrode portions 216c, 217c similar to the linear trap electrode arrangement 204a. Using the side electrode portion 216c as a non-limiting example, each side electrode portion 216c, 217c may include a plurality of (horizontal) electrode segments (two electrode segments shown represented by 218c). The two side electrode portions 216c, 217c, together with the two linear electrode portions 210c, 211c, may define a linear trap electrode arrangement 204c. The electrode segments 218c are DC electrode segments to which one or more DC signal(s) may be applied to facilitate ion movement in the axial direction (y direction) when operated in the linear trap mode. In point trap mode, the electrode segments 218c may be set as DC or ground depending on the needs. As a non-limiting example, in point trap mode, the electrode segments 218c may be set as DC, by application of DC signal(s) thereto, for field compensation.

[0087] Each of the large electrode segments 241c, 244c may have a length of about 700  $\mu\text{m}$ . The large electrode segments in between the electrode segments 241c, 244c may be broken into three minor electrode segments of a length of about 244  $\mu\text{m}$  (see, for example, the three minor electrode segments 226c, 242c, 243c for the electrode portion 211c). Each of the minor electrode segments 226c, 228c, 242c, 243c, (see also electrode segments 226b, 228b of FIG. 2B) may have a length of about 244  $\mu\text{m}$ . The central minor electrode segment of the electrode portion 212c may further be divided into even smaller electrode segments 220c, 222c, 224c. Each of the smallest electrode segments 220c, 222c, 224c (see also electrode segments 220b, 222b, 224b of FIG. 2B) may be a square segment with a dimension of about 80  $\times$  80  $\mu\text{m}$ , which may be provided for point trap implementation.

[0088] In various embodiments, and referring to the point trap electrode arrangement 202c as a non-limiting example, the minimum number for the innermost electrode segment (e.g., 220c) may be one, the minimum number for the inner electrode segments (e.g., 222c, 224c, 226c, 228c) may be four to ensure or enable feasible integration with the linear trap electrode arrangement 204c, while the minimum number for the outermost electrode segments (e.g., three parallel electrode segments 242c, three parallel electrode segments 243c, part of the side

electrode portion 216c, and part of the side electrode portion 217c) may be eight to ensure or enable feasible integration with the linear trap electrode arrangement 204c.

[0089] While FIG. 2C shows that the point trap electrode arrangement 202c is provided at a central portion of the integrated trap electrode arrangement 240c, it should be appreciated that the point trap electrode arrangement 202c may be provided at any location along the y direction. Further, while FIG. 2C shows a single point trap electrode arrangement 202c, it should be appreciated that there may be provided two or more point trap electrode arrangements. The plurality of point trap electrode arrangements or point traps may be arranged in a straight line or coaxially with one another to facilitate integration with the linear trap electrode arrangement 204c or linear trap.

[0090] FIGS. 3A to 3D show the device 200c of FIG. 2C having an integrated ion trap operating in a point trap mode, illustrating the integrated trap electrode arrangement 240c working in the point trap mode.

[0091] As shown in FIG. 3A, the point trap mode may be enabled by applying two RF signals with the same phase but of different amplitudes to the point trap electrode arrangement 202c. A first RF signal, RF1, may be applied to the surrounding (neighbouring) electrode segments 222c, 224c, 226c, 228c (which make up an electrode region), while a second RF signal, RF2, may be applied to the (central) square electrode segment 220c. The remaining electrodes or electrode segments may be kept or maintained as DC or ground. The encircled electrode segments 220c, 222c, 224c, 226c, 228c may be used to produce a trapping field with a local minimum in the form of a point RF null, whereas the square electrode segment 220c may be used to adjust the potential minimum height or the height (in the z direction) of the point RF null. The point RF null is the minimum pseudopotential point of field resulting from both RF1 and RF2 being applied to the electrode segments 220c, 222c, 224c, 226c, 228c. The use of two RF signals, RF1 and RF2, having different amplitudes may facilitate tuning of the point RF null height. Having RF signals of the same phase may minimise or avoid introducing anti-confinement potential.

[0092] The distribution of electric field may be modelled and the results are shown in FIGS. 3B and 3C. FIG. 3B shows the electric field distribution in the x-z cut-plane. A trapping point (RF null) 360 may be observed above the ion trap surface. As may be observed, the RF null 360 is a point RF null 360 at a distance or height above the electrode or device surface. FIG. 3C shows

the electric field distribution across the RF null 360 in the x-y cut-plane, including a zoom-in image showing the point RF null 360 in the geometry center. The white dashed arrows in FIGS. 3B and 3C show the directions of increasing electric field.

[0093] The relationship between the ion-electrode distance and the amplitude of the second RF signal, RF2, is illustrated in FIG. 3D which shows a plot of the ion-electrode distance as a function of the RF2 amplitude (RF1 has a constant amplitude of about 100 V). Both RF1 and RF2 signals have a frequency of about 30 MHz. The ion-electrode distance is approximately 55  $\mu\text{m}$  (marked with an asterisk in FIG. 3D) when no RF2 is applied. As may be observed in FIG. 3D, the distance or height of the RF null 360 may be adjusted from about 20  $\mu\text{m}$  to about 120  $\mu\text{m}$  by changing the potential or amplitude of RF2. The dashed arrows in FIG. 3D show the directions from RF2 = -180V to RF2 = 60V. An even larger adjustment range may be achieved if the trap is working in a cryogenic environment in which only a lower trapping depth may be needed. As described, the trapping height adjustment in the point trap mode may be facilitated by in-situ moving of the point RF null 360, instead of tuning DC potentials. This may minimise the excess micromotion induced by the position offset between ion(s) (not shown) and the point RF null 360. An ion shuttling path perpendicular to the trap surface may thus be built or enabled by continual or continuous RF voltages tuning of RF2 applied to the square electrode segment 220c.

[0094] FIGS. 4A to 4D show the device 200c of FIG. 2C having an integrated ion trap operating in a linear trap mode, illustrating the integrated trap electrode arrangement 240c working in the linear trap mode.

[0095] Referring to FIG. 4A, by applying an RF signal or potential to the linear trap electrode arrangement 204c, the integrated trap of the device 200c may work in the linear mode and generate a linear RF null (or RF null line) (see linear RF null 460c of FIG. 4C). An RF signal, RF3, may be applied onto two parallel (and symmetric) electrodes, in the form of linear electrode portions 210c, 211c. RF3 may be applied to the electrode segments 226c, 228c, and the electrode segments 241c, 242c, 243c, 244c of the linear electrode portions 210c, 211c. The remaining electrodes or electrode segments may be kept or maintained as DC or ground. As a non-limiting example, with the electrode dimensions described herein, the linear trap may provide a constant ion-electrode distance of about 75  $\mu\text{m}$ .

[0096] One or more ions may be trapped at the linear RF null above the linear trap electrode arrangement 204c. The (horizontal) (DC) electrode segments (five electrode segments are shown represented by 218c in FIG. 4A) are used to move the ion(s) along the linear RF null in the linear trap mode. During operation, one or more DC signals may be applied to the two side electrode portions 216c, 217c, or the electrode segments 218c thereof. The DC signal(s) may be tuned, for example, by varying the amplitude or potential of the DC signal(s), to cause one or more ions trapped at the linear RF null to move along the linear RF null. Ion shuttling in the axial direction in a linear trap, and the control thereof, is a well-established technique, and, therefore, the corresponding description has not been included herein.

[0097] As electrode segments have been incorporated for point trap implementation (or mode), it may be necessary to evaluate the influence from inter-electrode gaps to the electric field distribution in the axial direction (i.e., y direction). Due to the presence of gaps ( $2 \times 2 \mu\text{m}$ ) between the electrode segments 222c and 220c, and between the electrode segments 224c and 220c, the central three electrodes 214c are not continuous, which may affect the electric field distribution. The distribution of electric field may be modelled and the results are shown in FIGS. 4B and 4C. FIG. 4B shows the electric field distribution in three parallel x-z cut-planes, located respectively at  $y = 0$  and  $y = \pm 700 \mu\text{m}$ . As may be observed, for each x-z cut-plane, there is an RF null 460. FIG. 4C shows the electric field distribution across the RF null 460 in the y-z cut-plane ( $x = 0$ ). A uniform RF null line (or linear RF null) 460c may be observed above the trap surface. The linear RF null 460c may be located over or above the electrode portion 212c. Ion(s) may be trapped at the linear RF null 460c, and in response to tuning of DC potentials applied to the electrode segments 218c, may be moved or shuttled along the linear RF null 460c.

[0098] The pseudopotential distribution along the RF null line 460c may be extracted. FIG. 4D shows the pseudopotential distribution as a function of axial distance along the linear RF null 460c of the linear trap above the trap surface. It may be observed that the maximum fluctuation may be less than 0.2 meV. In the trap region ( $\sim 244 \mu\text{m}$  in length) that accommodates two inter-electrode gaps (see inset of FIG. 4D) - one gap between the electrode segments 222c and 220c, and another gap between the electrode segments 224c and 220c, no excess fluctuation (see shaded region in FIG. 4D) may be observed. This indicates that a

barrier-free ion shuttling path parallel to the trap surface (e.g., in the axial y direction) may be built or enabled.

[0099] FIGS. 5A to 5D show the device 200c of FIG. 2C having an integrated ion trap operating in a combination mode, illustrating the integrated trap electrode arrangement 240c working in the combination mode.

[0100] The device 200c having the integrated ion trap may simultaneously feature the functions or modes of point trap and linear trap (i.e., operating in the combination mode), where RF signals are applied to the integrated trap electrode arrangement 240c to operate point and linear traps simultaneously. The point trap region enabled by or corresponding to the point trap electrode arrangement 202c and the linear trap region enabled by or corresponding to the linear trap electrode arrangement 204c may be respectively located at the geometry center and the remaining parts at two ends.

[0101] Referring to FIG. 5A, a first RF signal, RF1, may be applied to the surrounding (neighbouring) electrode segments 222c, 224c, 226c, 228c (which make up an electrode region), a second RF signal, RF2, may be applied to the (central) square electrode segment 220c, and a third RF signal, RF3, may be applied to the electrode segments 241c, 244c of the two linear electrode portions 210c, 211c. RF3 may be independent to RF1 and RF2. The remaining electrodes or electrode segments may be kept or maintained as DC or ground.

[0102] The signal RF3 may or may not have the same phase as the signals RF1 and RF2. The signal RF3 may or may not be of a different amplitude to one or more of the signals RF1 and RF2. RF3 may be independent from RF1 and RF2. Two independent trapping fields may be created: one from RF1 and RF2, and the other from RF3. It should be appreciated that RF3 may be a third RF signal, or may be identical to RF1 or RF2.

[0103] The distribution of electric field may be modelled and the results are shown in FIGS. 5B and 5C. For the purpose of modelling the electric field distribution, the signals RF1, RF2, RF3 are in same phase. However, it should be appreciated that RF3 may have a different phase to RF1 and RF2 since there are two independent trapping fields. FIG. 5B shows the electric field distribution in three parallel x-z cut-planes, located respectively at  $y = 0$  and  $y = \pm 700 \mu\text{m}$ . As may be observed, for each x-z cut-plane, there is an RF null 560b, 561b. However, the electric field for the middle x-z cut-plane (corresponding to the point trap region) providing the RF null 560b is slightly different than the electric fields for the x-z cut-planes of the linear trap

region providing the RF nulls 561b. The regions can, however, be more clearly differentiated from a view of a z-y cut-plane. FIG. 5C shows the electric field distribution in the y-z cut-plane ( $x = 0$ ), where the linear trap region has a respective uniform RF null line 561c while the point trap region has a single RF null point 560c.

5 **[0104]** Interference between the linear trap region and the point trap region may be evaluated. FIG. 5D shows the pseudopotential distribution as a function of axial distance (y direction) along the RF null 560c, 561c above the trap surface. As may be observed, the pseudopotential in the axial direction may decline rapidly from the point trap region to the linear trap region. A buffer region, where the electrode segments 242c, 243c of the linear electrode portions 210c,  
10 211c are and without any RF signals being applied thereto, may be introduced in between the point trap region and the linear trap region to minimise interference between the point trap and linear trap regions.

**[0105]** During operation, one or more DC signals may be applied to the two side electrode portions 216c, 217c, or the electrode segments (five electrode segments are shown represented  
15 by 218c in FIG. 5A) thereof. The DC signal(s) may be tuned, for example, by varying the amplitude or potential of the DC signal(s), to cause one or more ions trapped at the RF null line 561c to move along the RF null line 561c from the point trap region to the linear trap region, and vice versa. At the point RF null 560c, a trapped ion may be movable in the height direction by tuning the signal RF2, for example, by varying the amplitude or potential of RF2,  
20 to change the distance of the point RF null 560c to the device surface.

**[0106]** It should be appreciated that description in relation to the point trap mode in the context of FIGS. 3A to 3D and the linear trap mode in the context of FIGS. 4A to 4D may be applicable to the combination mode.

**[0107]** In a 2D shuttling process, certain or selected ions (e.g., located at certain locations of the  
25 device) may first be shuttled along an axial direction by setting or tuning the DC potentials applied to the linear trap electrode arrangement in the linear trap mode to a position where the point trap or the point trap electrode arrangement is located so that the ions may be trapped above the point trap electrode arrangement. After that, the ion trapping height may be raised or dropped by the in-operation point trap. The remaining parts of the integrated trap which are not  
30 used for point trapping may still work as part of a linear trap if needed.

[0108] In the context of various embodiments, non-limiting examples of ions that may be trapped and shuttled may include Be<sup>+</sup>, Mg<sup>+</sup>, Ca<sup>+</sup>, Sr<sup>+</sup>, Cd<sup>+</sup>, Ba<sup>+</sup>, and Yb<sup>+</sup>.

[0109] Some isolated island electrodes may be accommodated in the integrated trap design of various embodiments. Isolated island electrodes are electrodes that are encircled by neighbouring electrodes and do not have direct access to perimeter bonding pads. The isolated island electrodes are determined by the surface trap geometry configuration. For example, referring to FIG. 2C, the innermost electrode (or electrode segment) 220c and the inner electrodes (or electrode segments) 222c, 224c, 226c, 228c for the point trap of various embodiments are all isolated. Wire bonding to access them must fly over other electrodes, which may not be feasible. In reference to that, through silicon via (TSV) together with redistribution layer (RDL) on an interposer may be employed for electrical feedthrough in place of known bonding wires. Since different signals (RF and DC) may be transmitted onto certain electrodes alternately for the conversion between linear trap and point trap, TSVs and RDL may significantly ease the complex signal routing. Further, TSVs and RDL may also benefit the disruption-free laser path as well as low parasitic components.

[0110] A non-limiting example of a fabrication process for an integrated ion trap with TSVs and interposer is illustrated schematically in FIGS. 6A to 6M. The process may be divided into three parts, which are the front-side TSV trap fabrication (see FIGS. 6A to 6D), the back-side TSV trap fabrication (see FIGS. 6E to 6H), and the interposer fabrication (see FIGS. 6I to 6L). The entire fabrication may be compatible with standard CMOS (complementary metal-oxide semiconductor) back end techniques. For the implementation of TSVs, the integrated ion trap itself requires silicon as a substrate. On the other hand, glass may be used as the interposer substrate to minimise RF loss.

[0111] FIGS. 6A to 6D show a front-side fabrication process of the integrated trap, where deposition of SiO<sub>2</sub> (silicon dioxide), blind via etching, barrier and seed layer in-via deposition, Cu (copper) filling, SiO<sub>2</sub> and electrode patterning are conducted in sequence. As shown in FIG. 6A, a SiO<sub>2</sub> layer 662 may be deposited on a silicon (Si) substrate 660. As shown in FIG. 6B, vias (two vias are represented by 664) are etched through the SiO<sub>2</sub> layer 662 and into the substrate 660. Referring to FIG. 6C, a barrier layer (not shown), e.g., a nickel (Ni) layer, and a seed layer (not shown), e.g., a copper (Cu) layer may then be deposited in the vias 664, followed by Cu filling 666 in the vias 664. A polishing process may be carried out. As an

alternative non-limiting example, the Cu filling 666 may be replaced by tungsten as the via filling. Referring to FIG. 6D, after SiO<sub>2</sub> layer 662 patterning and etching, a layer 668 of Cu, and a (top) layer 670 of gold (Au) may be deposited as surface electrodes (one electrode being represented by 672). The gold layer 670 may help to protect the inner electrodes where active metal (e.g., Cu) may be used. For example, the gold layer 670 may help to protect the Cu layer 668 from oxidation.

**[0112]** FIGS. 6E to 6H show a back-side fabrication process of the integrated trap, where grinding, SiO<sub>2</sub> deposition, polishing, etching, backside RDL patterning, polyamide patterning and micro bump deposition are conducted in sequence. Referring to FIG. 6E, a handle wafer 674 may be attached to, via an adhesive or a glue 676, to the front-side (i.e., the side with the electrodes 672) of the substrate 660 to allow easier handling of the substrate 660 for back-side processing. A grinding, polishing together with etching process may then be carried out on the back-side of the substrate 660 to reach the vias 664, followed by deposition of a SiO<sub>2</sub> layer 678, and subsequently a polishing and etching process to expose the Cu filling 666. As a result, a plurality of through silicon vias (TSVs) 667 may be formed. As the device wafer or substrate 660 may be required to be thinned to approximately 100 μm to reveal the TSVs 667 at the backside, the handle wafer 674 may, therefore, be provided to support the substrate 660. The glue 676 is for temporary bonding of the substrate 660 and the handle wafer 674.

**[0113]** Referring to FIG. 6F, a layer 680 of Cu RDL (backside) may then be formed using lithography-defined electroplating. Referring to FIG. 6G, a layer 682 of polyamide may be formed to cover the SiO<sub>2</sub> layer 678 and the RDL 680. The polyamide layer 682 may help to protect the Cu RDL 680 from oxidation. The polyamide layer 682 may then be patterned and etched to form openings (two openings being represented by 684) that are aligned with the RDL 680 and expose the RDL 680. As an alternative non-limiting example, the polyamide layer 682 may be replaced by SiO<sub>2</sub> although there may be challenges as the corresponding process may be complex and the thermal budget for the wafer backside has to be considered. Referring to FIG. 6H, the openings 684 may be filled with Cu, followed by deposition of micro bumps (two micro bumps being represented by 686) to be electrically coupled to the RDL 680 and the vias 664 with the Cu filling 666. The handle wafer 674 and the glue 676 may be removed, e.g., by mechanical debonding followed by cleaning. An integrated trap 688 having TSVs 667 and backside RDL 680 may thus be formed.

[0114] FIGS. 6I to 6L show a fabrication process of a glass interposer, where barrier and seed layer deposition, RDL patterning, polyamide patterning and under bump metallization deposition are conducted in sequence. Referring to FIG. 6I, a glass substrate 690 may be employed. A barrier layer (not shown), e.g., a nickel (Ni) layer, and a seed layer (not shown), e.g., a copper (Cu) layer may then be deposited on the glass substrate 690. Referring to FIG. 6J, a layer 691 of Cu RDL may then be formed on the barrier and seed layers using lithography-defined electroplating. Referring to FIG. 6K, a layer 692 of polyamide may be formed on the glass substrate 690 and the RDL 691. The polyamide layer 692 may then be patterned and etched to form openings (one opening being represented by 693) that are aligned with the RDL 691 and expose the RDL 691. Referring to FIG. 6L, an under bump metallisation deposition process may be carried out by depositing Cu in the openings 693 and on the polyamide layer 692, followed by depositing a layer 694 of Au, and subsequently followed by patterning and etching of the layer 694 of Au to form an interposer 696.

[0115] FIG. 6M shows the fabricated trap 688 and the interposer 696 being aligned and bonded together. This allows electrical interconnection between the integrated trap 688 and the interposer 696. As described above, the interposer 696 may be used to locate the TSV integrated trap 688. The TSVs 667 and the micro bumps 686 at the wafer backside of the integrated trap 688 may be connected to the RDL 691 on the interposer 696.

[0116] It should be appreciated that any number of electrical interconnections (e.g., TSVs 667, RDL 680, micro bumps 686, RDL 691, etc.) may be formed.

[0117] With the introduction of TSVs and interposer, the scale-up of the integrated ion trap of various embodiments may be relatively straightforward. By aligning multiple integrated traps together, one laser beam may be able to address (all) the ions with a raised trapping height as shown in FIGS. 7A and 7B which schematically illustrate scaling up of the integrated ion trap of various embodiments. FIG. 7A shows the electric field distribution in three parallel x-z cut-planes, located respectively at  $y = 0$  and  $y = \pm 700 \mu\text{m}$ , for two integrated ion traps 740a, 741a aligned side by side. As may be observed, there may be multiple RF nulls (four RF nulls being represented by 750a). FIG. 7B shows a schematic view of large-scale laser addressing, using a laser beam 760, of ions (four ions being represented by 706) trapped using point trap electrode arrangements 702b, 703b from two different integrated traps 740b, 741b. Further, provided ions at different point traps may be interconnected (e.g., through optical fibers or via conducting

interconnects), high fidelity quantum operations in an extremely large scale are foreseen, potentially opening up new opportunities for quantum information processing.

**[0118]** It should be appreciated that the geometry dimension of the point trap and/or the linear trap may be varied and not limited to those of FIGS. 2A to 2C. The trapping height adjustment range may be changed accordingly. Further, the scaling up of integrated ion trap may be diverse (e.g., 1D array, 2D array, X or Y junction layout).

**[0119]** It should be appreciated that the fabrication process for TSV integrated ion trap may be varied, compared to the process of FIGS. 6A to 6M. Further, the materials of the electrode and/or the dielectric layers may be any possible or suitable materials. The TSVs and/or the interposer may be replaced by multilayer metallisation underneath the electrodes.

**[0120]** As described above, the techniques disclosed herein may modify the geometry of point trap from the known circular geometry to a square geometry and may integrate the point trap with a linear trap to enable two-dimensional ion shuttling. After integration, the integrated trap may work in three modes, which are the linear trap mode, the point trap mode and the combination mode. The conversion between the different modes may be simply achieved by switching the potentials of the corresponding surface electrodes. TSVs and interposer may be used for electrical signal feedthrough, which may further boost the scalability of the integrated ion trap. The techniques disclosed herein may have immediate applications for large-scale quantum information processing.

**[0121]** Various embodiments may provide a surface electrode ion trap, where ions are trapped above the surface. Also, the ion-electrode distance may be adjustable for certain or selected ions (e.g., located at certain locations of the device). Further, flexible interconnections may be used in place of bonding wires.

**[0122]** Various embodiments may employ a square geometry to implement the trapping-height-tunable trap. Further, the square point trap may be integrated with a linear trap for large scale quantum information processing.

**[0123]** Various embodiments may allow for adjusting the height of the ions at certain locations. For example, an ion shuttling path that is perpendicular to the trap surface may be enabled in the integrated trap. Meanwhile, the ability for ion transport along the axial direction is maintained.

**[0124]** In various embodiments, the increased ion-surface distance at certain locations may reduce the heating rate to a comparable level obtained from traps working in cryogenic environment. The techniques disclosed herein can be used in any environment, and does not require a cryogenic environment, nor limited to a cryogenic environment.

- 5 **[0125]** The techniques disclosed herein may further increase the ion control capability, enabling a path that is perpendicular to the trap surface.

**[0126]** While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the  
10 appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

## CLAIMS

1. A device for controlling an ion, comprising:

a point trap electrode arrangement; and

a linear trap electrode arrangement,

wherein the device is operable in a first mode, a second mode, and a combination thereof,

wherein, in the first mode, the point trap electrode arrangement is configured to generate a first radio frequency (RF) field comprising a point RF null to trap the ion at the point RF null above a surface of the device, and wherein a distance of the point RF null to the surface is variable in response to a change in a potential of an RF signal applied to the point trap electrode arrangement, and

wherein, in the second mode, the linear trap electrode arrangement is configured to generate a second RF field comprising a linear RF null to trap the ion at the linear RF null above the surface, and wherein the ion is movable along the linear RF null in response to a change in a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement.

2. The device as claimed in claim 1, wherein the point trap electrode arrangement comprises a square electrode segment to which the RF signal is to be applied to.

3. The device as claimed in claim 2, wherein the point trap electrode arrangement further comprises an electrode region at least substantially surrounding the square electrode segment, the square electrode segment and the electrode region being configured to co-operatively generate the first RF field.

4. The device as claimed in claim 3, wherein the square electrode segment and the electrode region are arranged in a square geometry.

5. The device as claimed in any one of claims 1 to 4, wherein the linear trap electrode arrangement comprises two linear electrode portions arranged at least substantially parallel to one another, and

wherein the two linear electrode portions are configured to co-operatively generate the second RF field.

6. The device as claimed in claim 5,

wherein the linear trap electrode arrangement further comprises two side electrode portions to which the at least one DC signal is to be applied to, the two linear electrode portions being arranged in between the two side electrode portions, and

wherein, for each of the two side electrode portions, the side electrode portion comprises a plurality of electrode segments having longitudinal axes that are oriented in a direction different to longitudinal axes of the two linear electrode portions.

7. The device as claimed in any one of claims 1 to 6, further comprising:

a support structure to support the point trap electrode arrangement and the linear trap electrode arrangement,

wherein a plurality of through vias are formed in the support structure, and

wherein, for a respective through via of the plurality of through vias, the respective through via comprises an electrically conductive material electrically coupled to the point trap electrode arrangement or the linear trap electrode arrangement.

8. The device as claimed in claim 7, further comprising a redistribution layer electrically coupled to the plurality of through vias.

9. The device as claimed in any one of claims 1 to 8, further comprising:

a plurality of point trap electrode arrangements arranged coaxially,

wherein, for each point trap electrode arrangement of the plurality of point trap electrode arrangements, the point trap electrode arrangement is configured to, in the first mode, generate the first RF field comprising the point RF null to trap a respective ion at the point RF null above the surface, wherein the distance of the point RF null to the surface is variable in response to the change in the potential of the RF signal applied to the point trap electrode arrangement.

10. A method for forming a device for controlling an ion, comprising:  
forming a point trap electrode arrangement on a support structure; and  
forming a linear trap electrode arrangement on the support structure,  
wherein the device is operable in a first mode, a second mode, and a combination  
5 thereof,

wherein, in the first mode, the point trap electrode arrangement is configured to generate  
a first radio frequency (RF) field comprising a point RF null to trap the ion at the point RF null  
above a surface of the device, and wherein a distance of the point RF null to the surface is  
variable in response to a change in a potential of an RF signal applied to the point trap electrode  
10 arrangement, and

wherein, in the second mode, the linear trap electrode arrangement is configured to  
generate a second RF field comprising a linear RF null to trap the ion at the linear RF null  
above the surface, and wherein the ion is movable along the linear RF null in response to a  
change in a potential of at least one direct current (DC) signal applied to the linear trap  
15 electrode arrangement.

11. The method as claimed in claim 10, wherein forming the point trap electrode  
arrangement comprises forming a square electrode segment to which the RF signal is to be  
applied to.

12. The method as claimed in claim 11, wherein forming the point trap electrode  
arrangement further comprises forming an electrode region at least substantially surrounding  
the square electrode segment, the square electrode segment and the electrode region being  
configured to co-operatively generate the first RF field.

13. The method as claimed in claim 12, wherein the square electrode segment and the  
electrode region are arranged in a square geometry.

14. The method as claimed in any one of claims 10 to 13,  
wherein forming the linear trap electrode arrangement comprises forming two linear  
electrode portions at least substantially parallel to one another, and

wherein the two linear electrode portions are configured to co-operatively generate the second RF field.

15. The method as claimed in claim 14,

5 wherein forming the linear trap electrode arrangement further comprises forming two side electrode portions to which the at least one DC signal is to be applied to, the two linear electrode portions being arranged in between the two side electrode portions, and

wherein forming the two side electrode portions comprises forming, for each of the two side electrode portions, a plurality of electrode segments having longitudinal axes that are  
10 oriented in a direction different to longitudinal axes of the two linear electrode portions.

16. The method as claimed in any one of claims 10 to 15, further comprising:

forming a plurality of through vias in the support structure,

15 wherein, for a respective through via of the plurality of through vias, the respective through via comprises an electrically conductive material electrically coupled to the point trap electrode arrangement or the linear trap electrode arrangement.

17. The method as claimed in claim 16, further comprising forming a redistribution layer electrically coupled to the plurality of through vias.

20 18. The method as claimed in any one of claims 10 to 17, further comprising:

forming a plurality of point trap electrode arrangements arranged coaxially,

25 wherein, for each point trap electrode arrangement of the plurality of point trap electrode arrangements, the point trap electrode arrangement is configured to, in the first mode, generate the first RF field comprising the point RF null to trap a respective ion at the point RF null above the surface, wherein the distance of the point RF null to the surface is variable in response to the change in the potential of the RF signal applied to the point trap electrode arrangement.

19. A method for controlling an ion comprising:

generating, via a linear trap electrode arrangement of a device for controlling the ion, a radio frequency (RF) field comprising a linear RF null to trap the ion at the linear RF null above a surface of the device;

5        adjusting a potential of at least one direct current (DC) signal applied to the linear trap electrode arrangement to move the ion along the linear RF null between the linear trap electrode arrangement and a point trap electrode arrangement of the device;

generating, via the point trap electrode arrangement, another RF field comprising a point RF null to trap the ion at the point RF null above the surface; and

10        adjusting a potential of an RF signal applied to the point trap electrode arrangement to vary a distance of the point RF null to the surface.

20. The method as claimed in claim 19, wherein adjusting the potential of the RF signal comprises adjusting the potential of the RF signal being applied to a square electrode segment  
15 of the point trap electrode arrangement.