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(54) **MODULAR MINIATURE CHARGED PARTICLE BEAM COLUMN**

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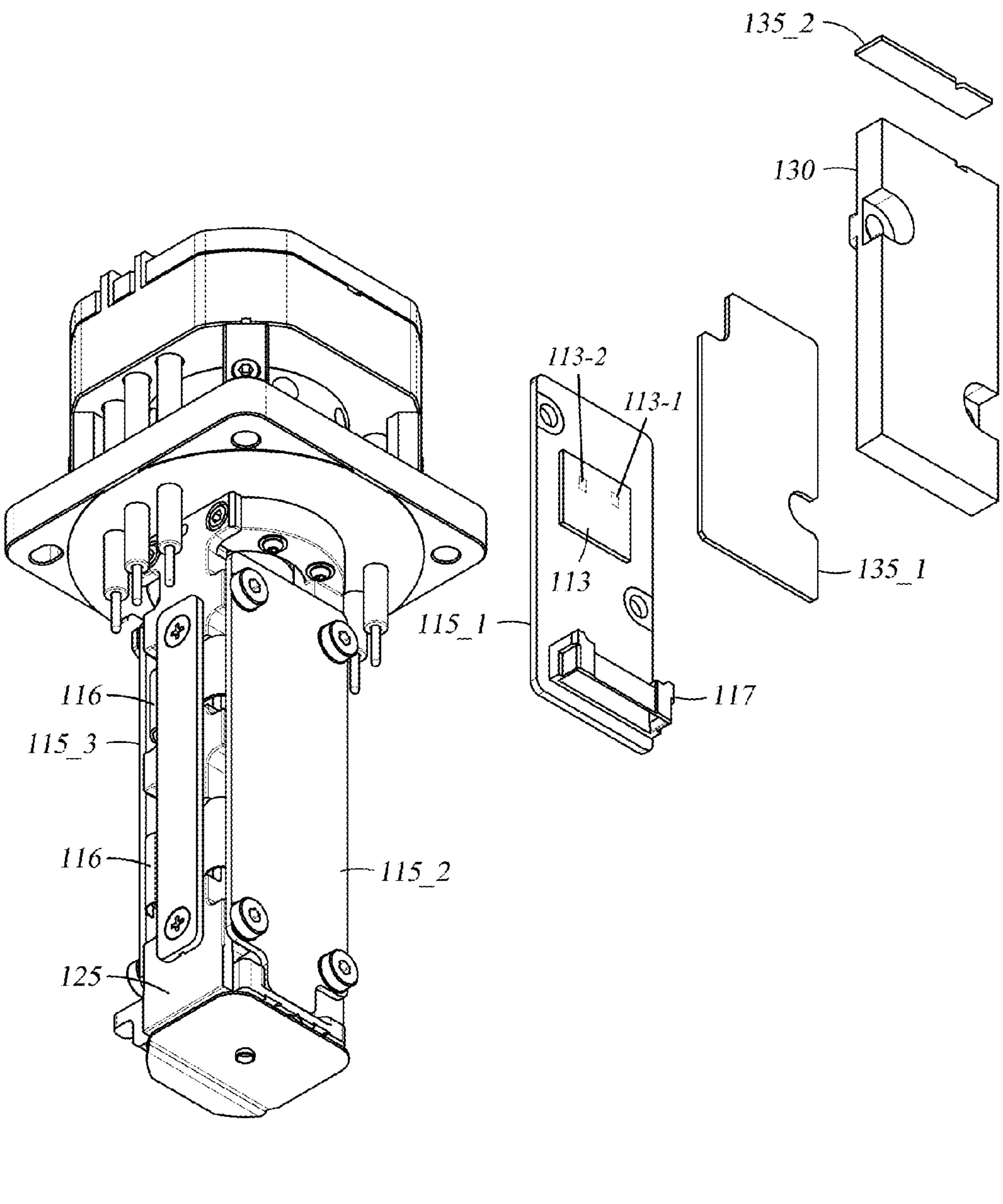
CPC ***H01J 37/302*** (2013.01); ***H01J 37/023*** (2013.01); *H01J 37/3174* (2013.01)

(57) **ABSTRACT**

Charged particle beam apparatus and methods are described herein. A charged particle beam apparatus herein includes a first column portion that has an emitter, a passively connectable power coupling coupled to the emitter, and a mechanical alignment structure coupled to the emitter, and a second column portion connected to the first column portion.



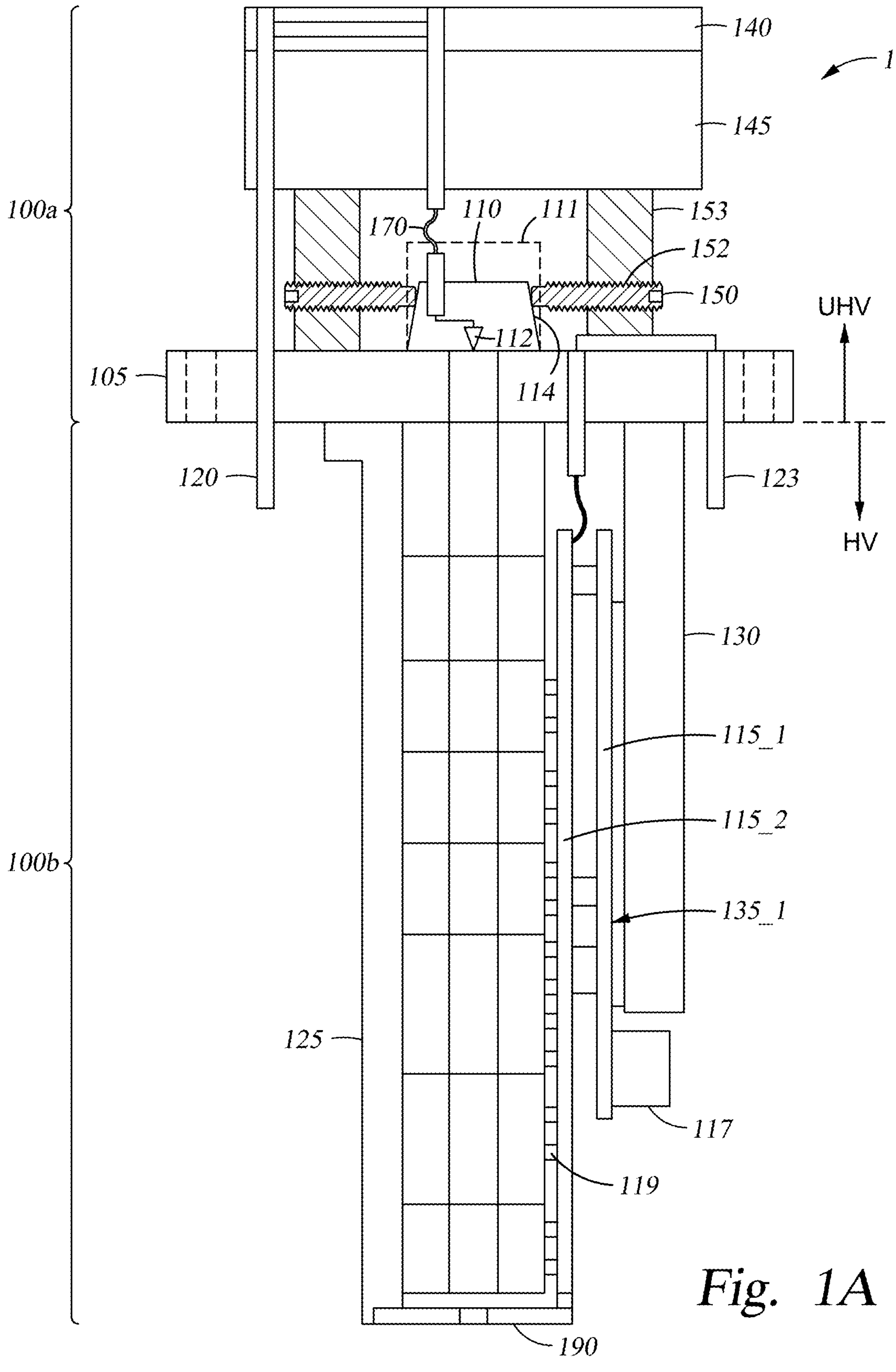

140
100
145
100a
153
110
111
170
152
150
UHV
112
105
114
120
123
HV
130
115_1
100b
115_2
135_1
125
117
119
190

Fig. 1A

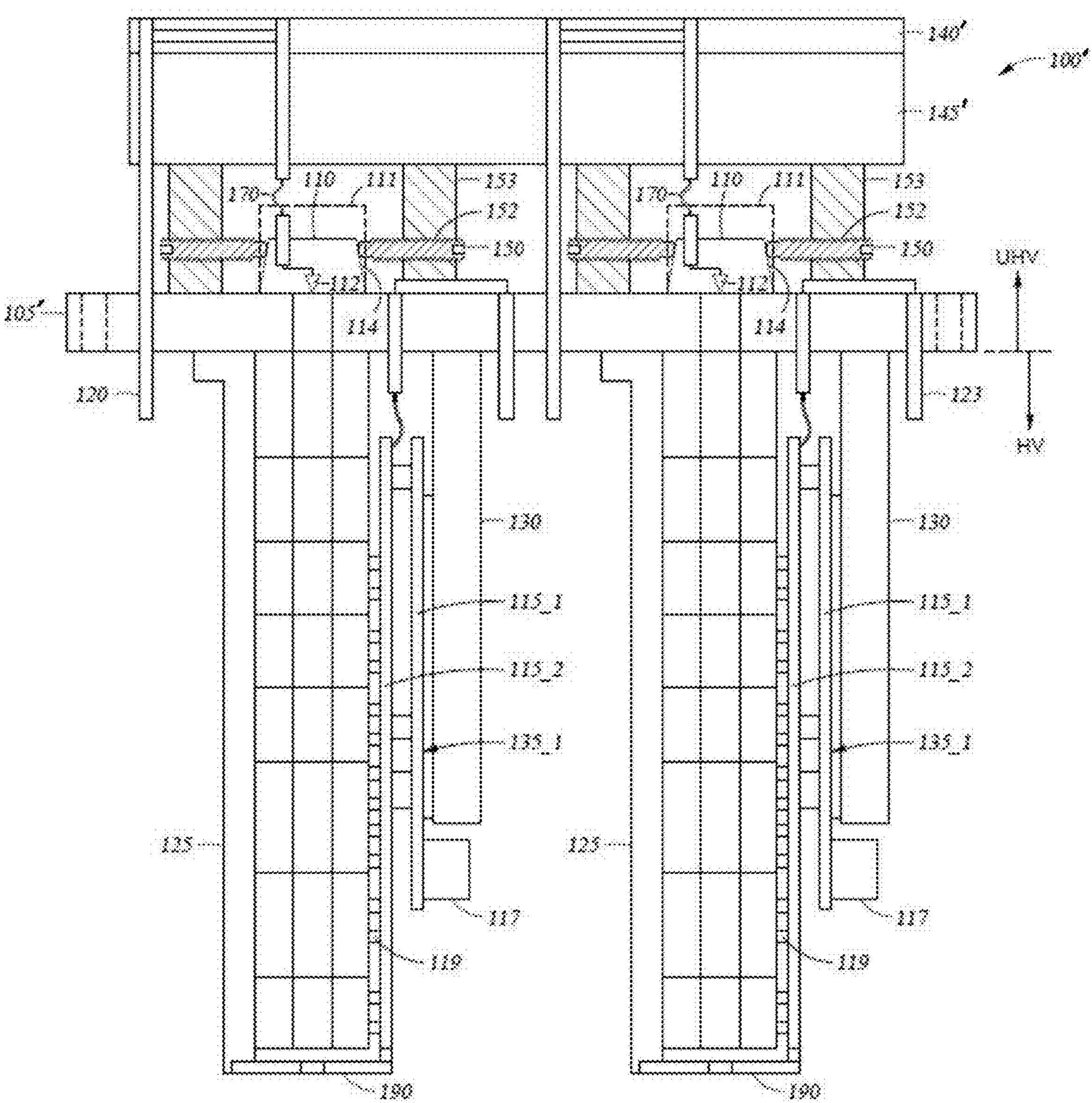

140'
100'
145'
170
110
111
153
152
150
112
114
105'
UHV
HV
120
123
130
115_1
115_2
135_1
125
117
119
190

Fig. 1B

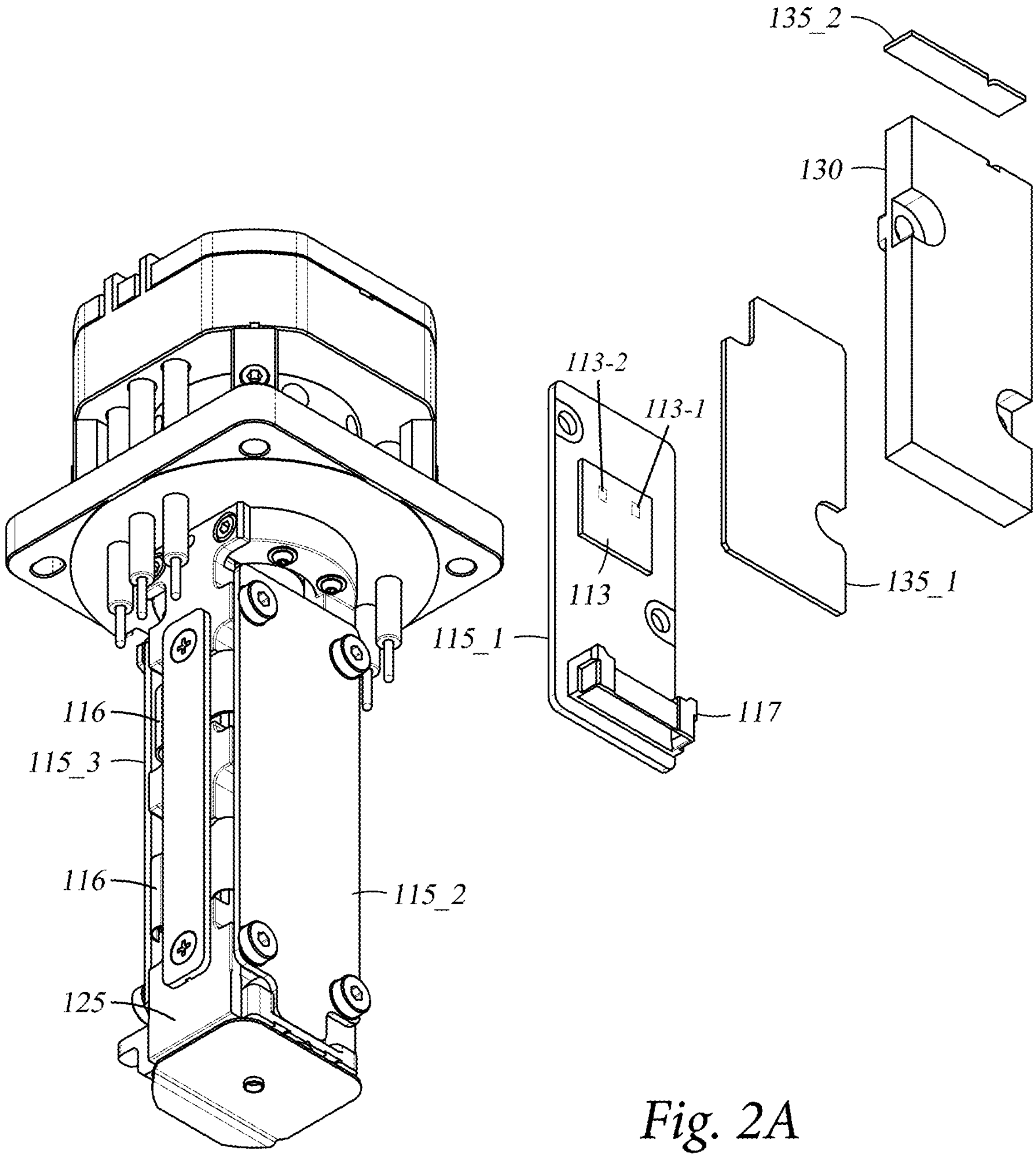


Fig. 2A

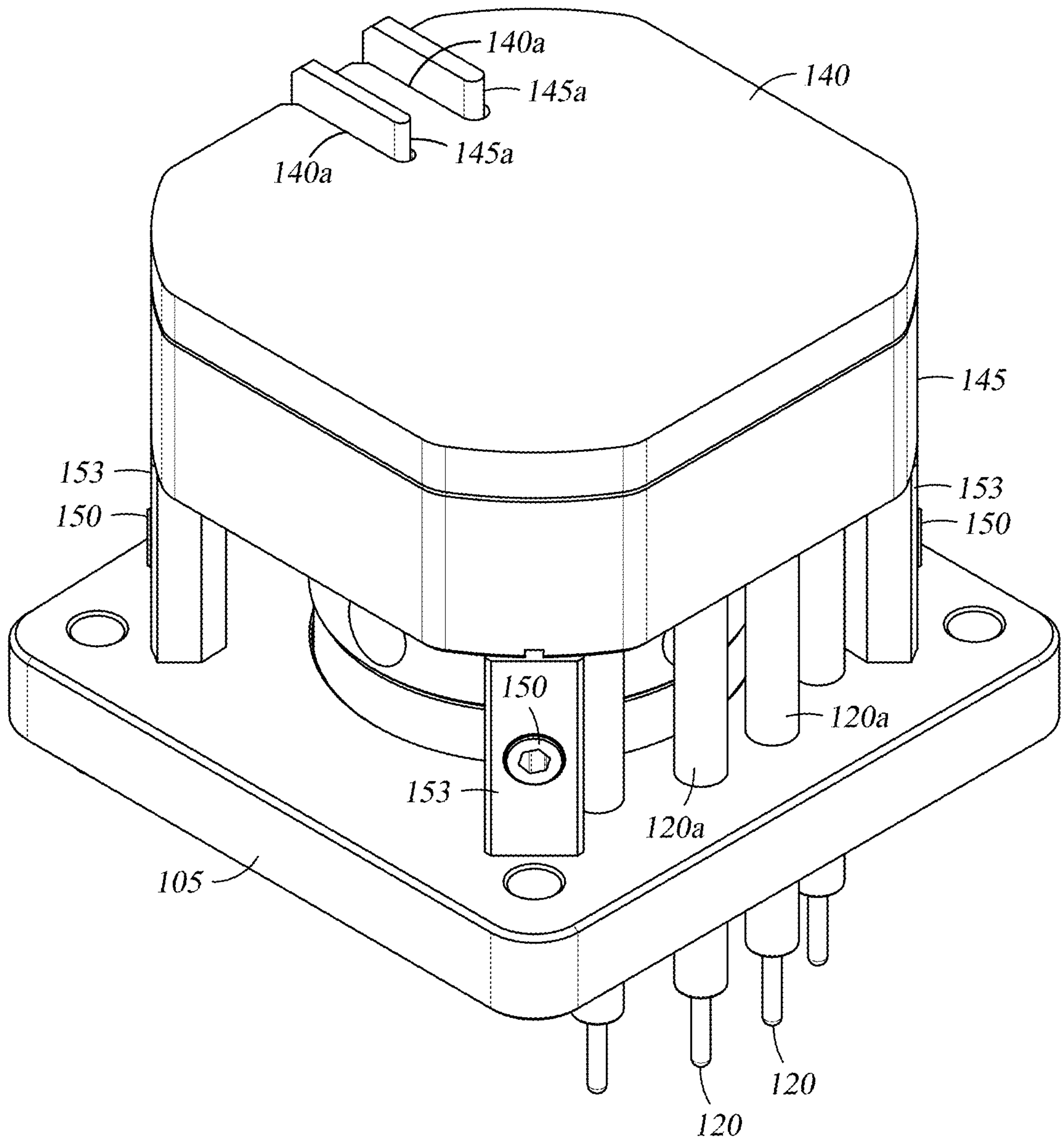

140a
140
145a
145a
140a
145
153
153
150
150
150
120a
153
120a
105
120
120

Fig. 2B

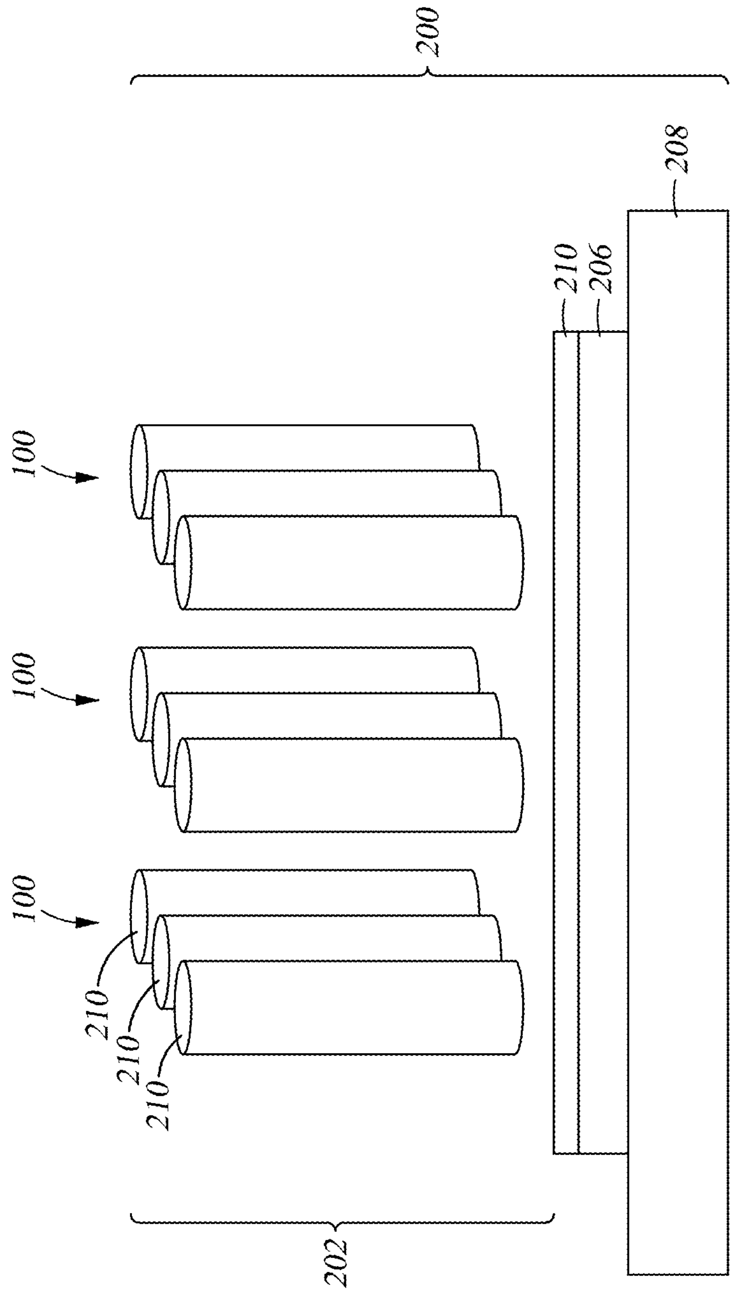
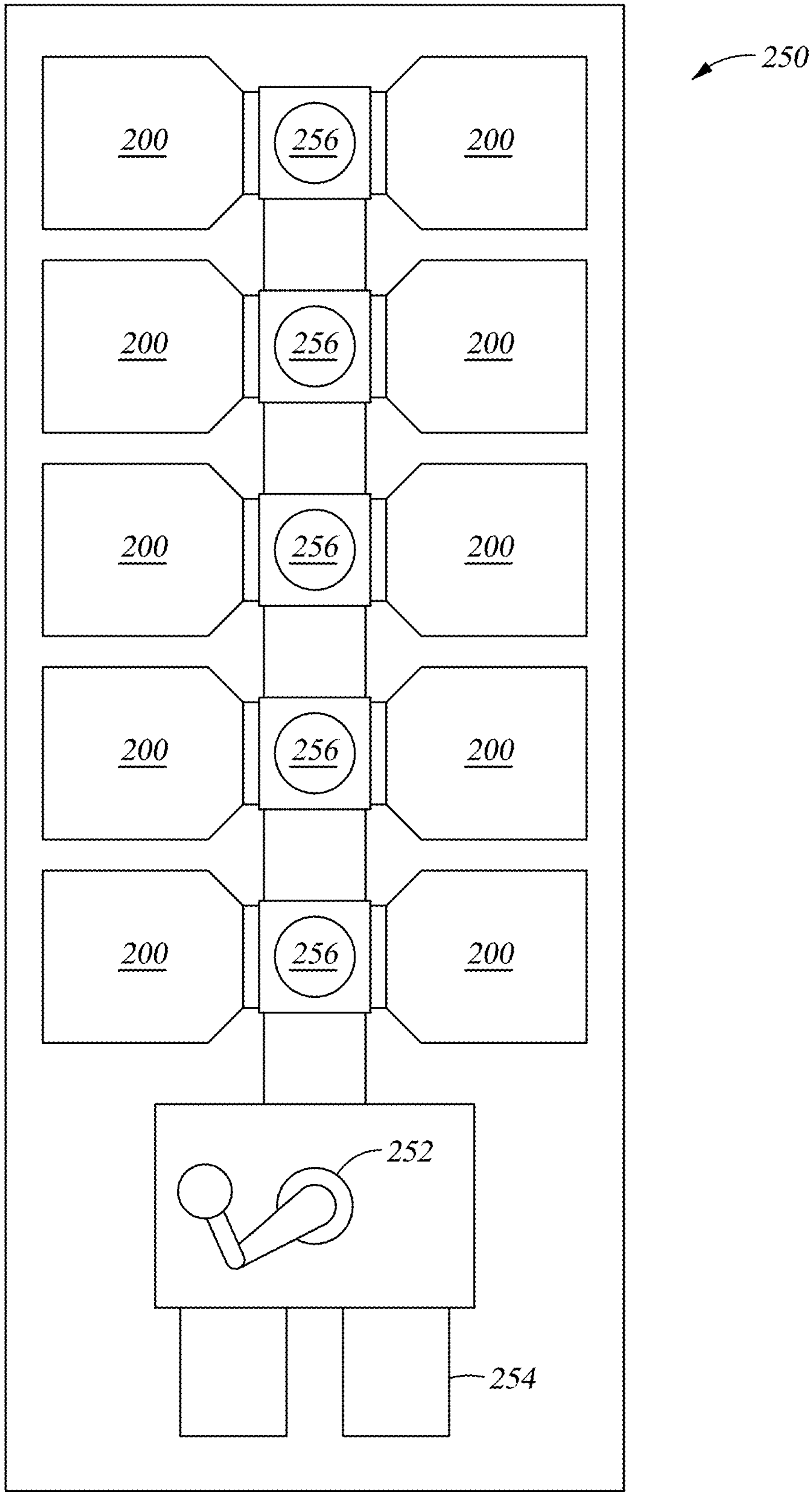


Fig. 3A


250
200
256
200
200
256
200
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256
200
200
256
200
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256
200
252
254

Fig. 3B

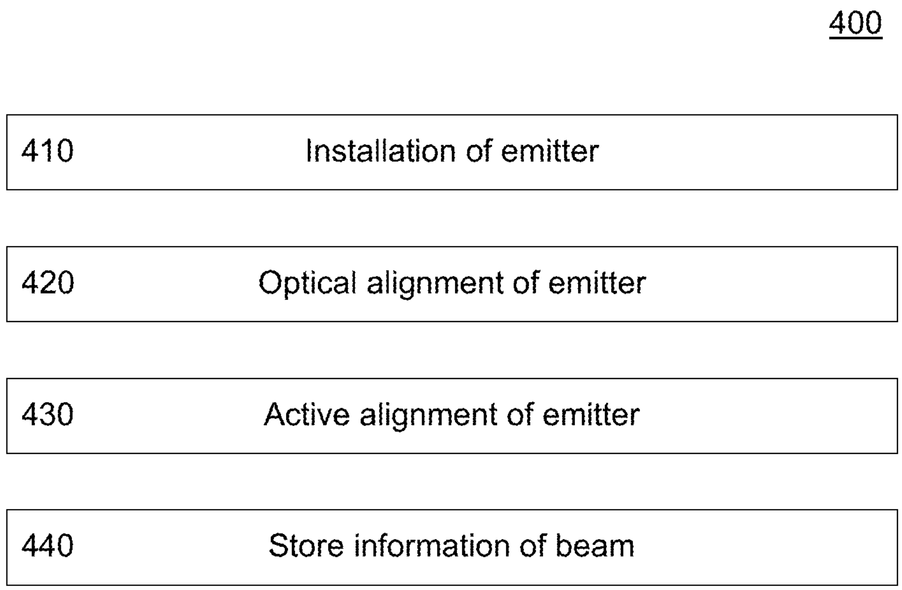
400
410 Installation of emitter
420 Optical alignment of emitter
430 Active alignment of emitter
440 Store information of beam

Fig. 4

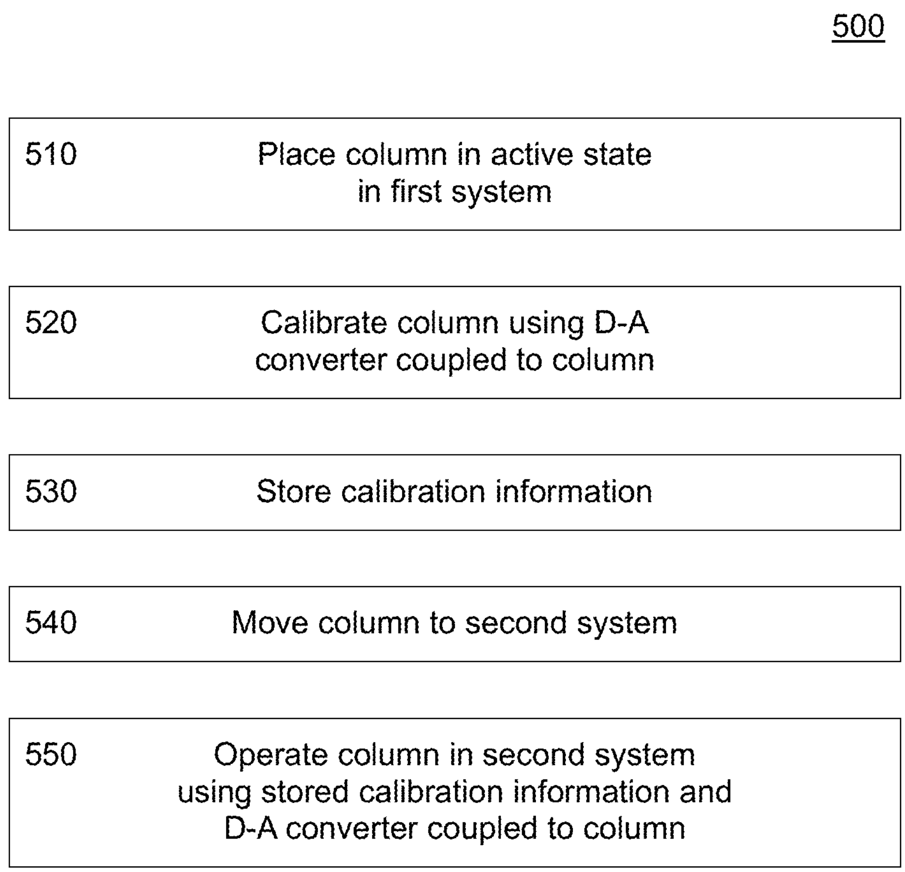
500
510 Place column in active state in first system
520 Calibrate column using D-A converter coupled to column
530 Store calibration information
540 Move column to second system
550 Operate column in second system using stored calibration information and D-A converter coupled to column

Fig. 5

MODULAR MINIATURE CHARGED PARTICLE BEAM COLUMN

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit from U.S. Provisional Patent Application No. 63/556,252, filed Feb. 21, 2024, which is incorporated herein by reference.

FIELD

[0002] Embodiments relate to a modular miniature charged particle beam column that produces a beam of charged particles, and associated methods.

BACKGROUND

[0003] Electron beam technologies are used in many manufacturing settings, most notably in semiconductor manufacturing. While electron beam techniques for lithography can enable highly customized variations on a semiconductor wafer, processing an entire workpiece using electron beam lithography can be prohibitively time consuming. Methods and apparatus are needed for faster, more cost-effective electron beam processing.

SUMMARY

[0004] Embodiments described herein provide a charged particle beam device, comprising a first column portion, comprising an emitter; a passively connectable power coupling coupled to the emitter; and a mechanical alignment structure coupled to the emitter; and a second column portion connected to the first column portion.

[0005] Other embodiments described herein provide a charged particle beam device, comprising a first column portion, comprising an emitter; a mechanical alignment structure coupled to the emitter; and a passively connectable power coupling coupled to the emitter; and a second column portion connected to the first column portion and comprising a control assembly and a digital controller attached to the control assembly.

[0006] Other embodiments described herein provide a charged particle beam device, comprising a first column portion, comprising an emitter; a mechanical alignment structure coupled to the emitter; and a passively connectable power coupling coupled to the emitter; a second column portion connected to the first column portion and comprising a control assembly and a digital controller attached to the control assembly; and a thermal conduit coupled to the digital controller.

[0007] Other embodiments described herein provide a charged particle beam device, comprising a first column portion comprising base plate to receive a charged particle emitter at a first side of the base plate; a second column portion comprising a control assembly, the second column portion connected to the first column portion on a second side of the base plate; and a circuit board comprising a digital control circuit on the second column portion.

[0008] Other embodiments described herein provide a method of operating a charged particle beam device, the method comprising generating an analog signal using a digital signal provided to a digital-to-analog converter, the digital-to-analog converter being coupled to the charged particle beam device in a portion of the charged particle beam device that is exposed to vacuum; and applying the analog signal to a beam-control element that is coupled to the charged particle beam device in the portion of the charged particle beam device that is exposed to vacuum.

[0009] Other embodiments described herein provide a method of configuring a charged particle beam device, the method comprising adjusting a position of an emitter in the charged particle beam device while evaluating the position of the emitter optically; operating the emitter in the charged particle beam device to produce a charged particle beam from the emitter, and evaluating an attribute of the charged particle beam; and storing information relating to the attribute of the charged particle beam in a memory coupled to the charged particle beam device.

[0010] Other embodiments described herein provide a method of operating a charged particle beam device, the method comprising generating an analog signal using a digital signal provided to a digital-to-analog converter that is coupled to the charged particle beam device while the charged particle beam device is installed in a processing system; and applying the analog signal to a beam-control element of the charged particle beam device while the charged particle beam device is installed in the processing system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Some example embodiments are illustrated, by way of example and not limitation, in the accompanying figures. In the figures, like reference numbers indicate like features, and features might not be drawn to scale.

[0012] FIG. **1**A is a schematic cross-sectional view of a modular miniature charged particle beam column according to an example embodiment.

[0013] FIG. **1**B is a schematic cross-sectional view of a modular miniature charged particle beam column apparatus according to an example embodiment.

[0014] FIG. **2**A is an exploded perspective view of the charged particle beam column of FIG. **1**A.

[0015] FIG. **2**B is a perspective view of an upper portion of the charged particle beam column of FIGS. **1**A and **2**A.

[0016] FIGS. **3**A and **3**B are system diagrams illustrating aspects of a system that includes a plurality of modular miniature charged particle beam columns according to an example embodiment.

[0017] FIG. **4** is a method diagram illustrating a method of aligning an emitter according to an example embodiment.

[0018] FIG. **5** is a method diagram illustrating a method of preparing a column according to an example embodiment.

DETAILED DESCRIPTION

[0019] Modular miniature charged particle beam columns are described herein that can be used for, e.g., maskless patterning of a workpiece such as a wafer, a semiconductor, optical, or optoelectronic package, an interposer, and the like. Such charged particle beam columns can be implemented as a group or array of multiple modular charged particle beam columns to allow parallel processing of a single workpiece by the multiple modular charged particle beam columns, e.g., multicolumn or multibeam processing. These modular charged particle beam columns can be described as “plug-and-play,” having features that allow for fast installation, short down-times, short mean time to repair (MTTR), and generally quick and easy deployment and replacement. The charged particle beam column can include features that reduce pump-down times and eliminate virtual leaks in a vacuum environment. Virtual leaks are sources that act to increase pressure in the vacuum environment, e.g., trapped gasses, components that volatilize or vaporize in the vacuum environment (such as chemical components of seals, coatings, or other parts), and the like. The charged particle beam column can be a modular component that simplifies installation and replacement of the charged particle beam column in a system. For example, some charged particle beam columns described herein are enhanced with features that facilitate alignment and/or calibration or other preparation.

[0020] FIG. **1**A is a schematic cross-sectional view of a charged particle beam column **100** according to an example embodiment. The column **100** is a modular, miniature charged particle beam column. The column **100** can have a size that enables use of multiple columns **100** arranged in a single processing chamber to process a single workpiece. In one case, nine columns **100** are arranged side-by-side in a processing chamber as a three-by-three array to act on a single 200 mm wafer, although it will be understood that more or fewer columns **100** can be arranged in a chamber and other sizes and types of workpieces can be processed. For example, in another case, 25 columns **100** are arranged side-by-side in a five-by-five array within a single processing chamber. The column **100** can have a lateral dimension, in a beam-controlling portion thereof, of about 25 mm and a length of about 125 mm, although it will be understood that the dimensions can vary.

[0021] In FIG. **1**A, the column **100** includes a first column portion **100***a* and a second column portion **100***b*. The first column portion **100***a* includes a source of charged particles. The source can be or include an emitter **110** that emits the charged particles. The second column portion **100***b* corresponds to a beam-controlling portion of the column **100**. The second column portion **100***b* includes a control assembly having one or more beam-control elements (e.g., elements that form, align, deflect, shape, and/or focus a beam of the charged particles) that form a control pathway traversed by the charged particles emitted from the emitter **110**.

[0022] The first column portion **100***a* can correspond to an ultra-high vacuum (UHV) environment. For example, the first column portion **100***a* can be deployed within the UHV environment, a UHV environment can be maintained within an interior of the first column portion **100***a*, or both. The second column portion **100***b* can correspond to a high vacuum (HV) environment. The column **100** can include a base member **105** that provides a sealed interface and divides the UHV environment from the HV environment. The base member **105** is shown and described herein as a plate, and referred to subsequently as a "base plate **105**," but the base member **105** could have a shape or structure that is not a plate, as such. Although FIG. **1**A illustrates the UHV and HV environments as respectively corresponding to a region above and below a lower surface of the base plate **105**, during operation of the column **100** some parts of the UHV and HV environments may extend in other regions. For example, the UHV environment may extend partially into the second column portion **100***b* in a center region (beam region) of the column **100**, while the rest of the second column portion **100***b* operates in the HV environment.

[0023] The emitter **110** can be an ion emitter or an electron emitter. The emitter **110** can be a thermal field emitter (TFE) that emits electrons at an emitter tip **112**. The electrons pass through an opening in the base plate **105** to the second column portion **100***b*. The emitter **110** can be disposed in the first column portion **100***a* and, in operation, is located in the UHV environment, while the second column portion **100***b* is located in the HV environment. The base plate **105** is penetrated by electrical conductors disposed through openings in the base plate **105** and sealed to the base plate **105** using sealant materials selected to isolate the UHV and HV environments.

[0024] During operation of the column **100**, the base plate **105** can maintain a pressure differential between the first column portion **100***a* and the second column portion **100***b* that is at least one order of magnitude. For example, the UHV environment can be maintained, during operation, at a first pressure, e.g., approximately 1E-9 Torr (1.3E-7 Pa) or less, while the HV environment is maintained, during operation, at a second pressure, e.g., approximately 1E-6 to 1E-8 Torr (1.3E-4 to 1.3E-6 Pa). In other cases, the UHV environment can have an operating pressure of about 1E-10 Torr (1.3E-8 Pa) while the HV environment has an operating pressure of 1E-9 Torr (1.3E-7 Pa) or more.

[0025] In another example, during operation of the column **100**, the base plate **105** can maintain a pressure difference between the first column portion **100***a* and the second column portion **100***b* while the emitter **110** operates in a first pressure environment that is at or near atmospheric pressure and the second column portion is at a higher or lower pressure than the first column portion. In another example, the first column portion **100***a* and the second column portion **100***b* operate in a same pressure environment. In the case that the first column portion **100***a* and the second column portion **100***b* operate in a same pressure environment, the base plate **105** may not provide a sealed interface between the first column portion **100***a* and the second column portion **100***b*, and/or no seal may be provided between the base plate **105** and a corresponding mounting surface.

[0026] One or more components of the second column portion **100***b* can be controlled using digital signals. The second column portion **100***b* can include circuitry to convert the digital signals into analog signals that control the charged particles originating from the emitter **110** and passing through the beam-control elements of the second column portion **100***b* to interact with a workpiece. In one case, at least some aspects of the circuitry are implemented as a digital controller **113** (FIG. **2**A). The digital controller **113** can include a digital-to-analog (D-A) converter **113-1** (FIG. **2**A). The D-A converter **113-1** converts a digital signal to an analog signal. The analog signal can be provided to a beam-control element of the control assembly. The beam-control element can be used to control or modify the trajectory of the charged particles, for example to form the charged particles into a beam. The digital controller **113** is electrically connected to the beam-control elements to deliver analog signals to the beam-control elements. The digital controller **113** having the D-A converter **113-1** can be mounted in the HV environment. For example, the digital controller **113** can be mounted to the support **125** or adjacent to the column **100** in the HV environment.

[0027] A printed circuit board (PCB) **115** or a plurality of the PCBs **115**, e.g., a first PCB **115_1** and a second PCB **115_2**, containing circuitry for controlling the beam-control elements can be coupled to the second column portion **100***b*. The PCB **115** can be electrically connected to one or more beam-control elements. The one or more PCBs **115** can include, or be connected to, the digital controller **113**, which can be mounted to, or adjacent to, the second column portion **100***b*. For example, the first PCB **115_1** can include the digital controller **113** as a part of the circuitry of the PCB **115_1** or as a component electrically connected to the PCB **115_1**.

[0028] The digital controller **113** can be a component that is electrically connected to the PCB **115**, or included in circuitry of the PCB **115**. The digital controller **113** can be wired to the PCB **115**, such that the digital controller **113** is a component located adjacent to the PCB **115** and physically connected to the PCB **115** only by wiring. Alternately, the digital controller **113** can be mounted to the PCB **115** and connected to circuits of the PCB **115** by soldering, wiring, or other electrical contact method. The digital controller **113** can be disposed proximate to the beam-control elements. By providing the digital controller **113** close to or local to the beam-control elements, a distance traveled by the analog signals between the digital controller **113** and the beam-control elements can be kept short, thus reducing opportunities for signal loss or noise to affect the analog signals. Such assemblies also enable the digital controller **113** to remain with the column **100** in the event the column **100** is removed from one system and installed in another system, or in the event the column **100** is operated in a test system and then moved to a production system.

[0029] The beam-control elements of the second column portion **100***b* can be included in a column structure that includes a support **125** that maintains structural integrity and operational relationships of the components of the second column portion **100***b*. The beam-control elements can be coupled with or mounted on the support **125**. The support **125** can be or include a bracket that extends along an axis of the second column portion **100***b*. The support **125** can be coupled to the base plate **105** or can be part of the base plate **105**. The column structure can include the support **125**, the beam-control elements, and the digital controller **113**, which can include the D-A converter or can be coupled to a D-A converter as a separate component or circuit.

[0030] Various configurations and combinations of the PCBs **115** can be implemented. One or more PCBs **115** can be mounted to the support **125**. Merely by way of example, FIG. **2**A illustrates three PCBs **115** coupled to the support **125**, with first and second PCBs (**115_1** and **115_2**, one stacked on the other) coupled to one side of the support **125** and a third PCB **115_3** coupled to an opposite side of the support **125**. The PCBs **115** can be electrically and physically connected together and/or connected to other components using, e.g., direct contacts therebetween, ribbon cables, and the like. FIG. **2**A shows two ribbon cables **116** connecting the second PCB **115_2** to the third PCB **115_3**. The second PCB **115_2** can be mounted to the support **125** and the first PCB **115_1** can be mounted to the second PCB **115_2**. In another example, the first PCB **115_1** and the second PCB **115_2** can be individually mounted to the support **125**. In another example, one or more of the PCBs **115** can be attached to a part of the second column portion **100***b* other than the support **125**.

[0031] The column **100** can have one or more analog signal-controlled beam-control elements that are calibrated. By including the digital controller **113** as part of the column **100**, as shown above, the calibration can be made more accurate, precise, and persistent as compared to a case in which the digital controller **113** is separate from the column **100**. A memory, e.g., a nonvolatile memory, can be provided on one or more of the PCBs **115** in the second column portion **100***b* and used to store calibration information, identification information, installation information, test information, any combination thereof, and/or other information. Calibration information can include settings applied to the analog beam-control elements of the column **100** that resulted in a beam condition within a tolerance. Test information can include beam conditions recorded during one or more tests of the column **100**. Identification information can include an identity of the column **100**, for example a numeric or alphanumeric code. The identification information can include a unique identifier to distinguish the column from other columns, e.g., from other visually identical columns. Installation information can include date information and identity of installer. By including the digital controller **113** and/or the memory as part of the column **100**, the column **100** can be made more modular by reducing the number of external components that are not "local" to the column **100** (e.g., by avoiding the need for an external or off-column digital controller **113** and/or memory). The column **100** having the digital controller **113** and/or memory thereon can be pre-calibrated in a test environment or test system prior to installation in a production system, which advantageously enables reductions in down time, MTTR, and the like when installing or changing the column **100** in the production system. In one example, power couplings of the first column portion **100***a* can provide power in a quick connection-disconnection structure to all components of the column **100**. In another example, power couplings of the second column portion **100***b* can provide power in a quick connection-disconnection structure to all components of the column **100**. In another example, power and signal couplings of the second column portion **100***b* can provide power and signals in a quick connection-disconnection structure to all components of the column **100**. The construction of the column **100** provides for quick installation of a complete modular, miniature charged particle column into a test system for testing or calibration, quick removal of the column from the test system, and quick installation of the column into a production system. It will be appreciated that such advantageous effects are multiplied when a plurality of the columns **100** is installed in a system.

[0032] One or more of the PCBs **115** can have a connector **117** thereon, which can provide low voltage supply and/or digital control connections. The connector **117** can be a ribbon cable connector, or other type of connector to supply power and/or control signals to the PCBs **115**. Interconnection of the PCBs **115**, as described above, enables the connector **117** to provide and/or control signals to all of the PCBs **115**.

[0033] One or more of the PCBs **115** can have electrical connectors **119** (FIG. **1**A). For example, one or more of the PCBs **115** can have electrical connections, made by the connectors **119**, to beam-control elements of the second column portion **100***b*. The connectors **119** can be resilient electrical contacts, such as pogo pins or the like, that extend between the second PCB **115_2** and beam-control elements of the second column portion **100***b*. Using resilient electrical contacts as electrical connectors enables application of compressive force between contacts of the PCBs **115** and contacts of the second column portion **100***b* to ensure that reliable electrical contact is maintained.

[0034] Heat removal from heat-generating components of one or more of the PCBs **115** can be enhanced by a heat transfer member, e.g., a thermal conduit **130**, which can be a heat sink. For example, the second column portion **100***b* can include the thermal conduit **130**, which can be thermally coupled to the base plate **105** to conduct heat to the base plate **105**. The thermal conduit **130** is disposed in thermal communication with circuitry or electronics on one or more of the PCBs **115**, and heat generated by the circuitry or electronics is conducted from the circuitry through the thermal conduit **130** to the base plate **105**. The base plate **105** can be thermally conductive, or can have a thermally conductive part or member, and can be thermally coupled to a cooling system that removes heat from the base plate **105**. The thermal pathway from circuitry of the PCBs **115** to a cooling system, thus configured, removes heat from the PCBs **115**.

[0035] In one example, the thermal conduit **130** is fixed to the support **125**, e.g., by one or more fasteners that engage the support **125**. FIG. **2**A shows the first PCB **115_1** and the second PCB **115_2**, each having generally planar shape, in parallel orientation and interposed between the thermal conduit **130** and the support **125**. In this case, the support **125** also has a generally planar shape and is disposed in perpendicular orientation to the first and second PCBs **115_1** and **115_2**. In another example, the thermal conduit **130** is fixed to one or more PCBs **115**.

[0036] A thermal coupling **135** or a plurality of thermal couplings **135** can be provided to enhance heat transfer. For example, referring to FIG. **2**A, a first thermal coupling **135_1** can be provided between, and in thermal communication with, each of the first PCB **115_1** and the thermal conduit **130**. The first thermal coupling **135_1** can be a solid material, an elastomer, or the like, that is thermally conductive, compliant, and vacuum-compatible. The first thermal coupling **135_1** can be a material that is electrically insulating. The first thermal coupling **135_1** can be a material such as a filled silicone that exhibits low outgassing under vacuum. As also shown in FIG. **2**A, a second thermal coupling **135_2** can be provided between, and in thermal communication with, each of an end of the thermal conduit **130** and a lower surface of the base plate **105**. The second thermal coupling **135_2** can be made of the same material as the first thermal coupling **135_1** or they can be made of different materials. The first thermal coupling **135_1** can be in direct physical contact with one or both of the first PCB **115_1** and the thermal conduit **130**. The second thermal coupling **135_2** can be in direct physical contact with one or both of the thermal conduit **130** and the base plate **105**.

[0037] A first conductor **120** or a plurality of the first conductors **120** and a second conductor **123** or a plurality of the second conductors **123** can be disposed through the base plate **105**. In this case, the two types of electrical conductors supply significantly different voltages for different purposes on the column **100**. For example, the second conductors **123** can supply a lower voltage than the first conductors **120**. The first conductors **120** and the second conductors **123** penetrate the base plate **105** to provide power while maintaining isolation of the UHV and HV environments.

[0038] The column **100** has power couplings that are passively connectable to power couplings of a processing chamber or a test chamber. In an example embodiment, one or more pins and/or one or more plugs attached to the column **100** are disposed to plug into or couple to corresponding electrical contacts provided in one or more mounting surfaces of the processing chamber or test chamber when the column **100** is inserted into, or coupled to, the processing chamber or test chamber. The passively connectable couplings of the column **100** enable the column **100** to be plugged into either a processing chamber or a test chamber having corresponding electrical contacts such that the column **100** can be easily transferred between a processing chamber and a test chamber. For example, using such structures, a column like the column **100** can be installed in a test chamber for testing and/or calibration, removed from the test chamber after testing and/or calibration, and then installed in a processing chamber, merely by plugging the column in, and unplugging the column from, either chamber.

[0039] In an example embodiment, one or more first conductors **120** and/or one or more second conductors **123** can be passively connected to a mounting surface, such as a lid, ceiling, mounting plate, or other surface of a processing chamber or a test chamber. For example, one or more first conductors **120** and/or one or more second conductors **123** can plug in to corresponding electrical contacts provided in a mounting surface when the column **100** is inserted into, or coupled to, a processing chamber. For example, a plurality of the first conductors **120** and/or the second conductors **123** can be substantially rigid, and extending in an insertion direction of the column **100** such that all of the plurality of first conductors **120** and/or the second conductors **123** plug in to corresponding electrical contacts when the column **100** is coupled to the processing chamber. The connector **117** of the PCB **115** can also be passively connectable. In one example, the first conductors **120**, the second conductors **123**, and the connector **117** all connect to corresponding electrical contacts of the processing chamber when the column **100** is inserted into the processing chamber. In another example, the connector **117** is not passively connectable, but the first and second conductors **120** and **123** are passively connectable. For example, the mounting surface of the processing chamber can have an opening to receive the second column portion **100***b*, and a plurality of electrical contacts surrounding the opening to receive at least one first conductor **120** and at least one second conductor **123**. The base plate **105** can be mounted to the mounting surface of the chamber using fasteners. Seal members can be disposed between the mounting surface and the base plate **105** to isolate an interior of the chamber.

[0040] In an example embodiment, the passively connectable power coupling provides power connections (e.g., one or more first conductors **120** and/or one or more second conductors **123**) on a second column portion side (e.g., HV side in FIG. **1**A) of the column **100** for supplying all power to the column **100**. In an example embodiment, the passively connectable power coupling provides power connections and signal connections (e.g., one or more first conductors **120**, one or more second conductors **123**, and one or more connectors **117**) on the second column portion side of the column **100** for supplying all power and signals to and from the column **100**.

[0041] The first column portion **100***a* can include conductors to supply a voltage to the emitter **110**. The conductors can include wiring traces in a wiring board (WB) **140** (FIG. **1**A), which can be a printed wiring board. The WB **140** can provide power, e.g., a high voltage, to the emitter **110**.

[0042] The first conductors **120** can be electrically connected to conductors of the WB **140** using a pin-and-receptacle arrangement. For example, each first conductor **120** can terminate in a pin structure, the WB **140** can have a plurality of corresponding receptacle structures, and the WB **140** can be electrically connected to the first conductors **120** by placing the WB **140** on the first conductors such that the pin structures engage and electrically connect with the receptacle structures.

[0043] Electrical connections can be made between the second column portion **100***b* and the WB **140** by the first conductors **120**. In other cases, one or more electrical connections to or from the WB **140** can be made using a flexible power conductor **170**, which can be a wire, a flexure, a pogo pin, a conductor that is compliant in one or more specific degrees of freedom, or another suitable compliant connector. In one example, the flexible conductor **170** is not a wire and no discrete wires are used to route high voltage connections. The flexible power conductor **170** can be coating-free. For example, the flexible power conductor **170** can be free of polymeric coatings or polymeric insulation that can cause a virtual leak in a vacuum environment. Electrical connections between the WB **140** and the emitter **110** can include conductive pins that are received in receptacles in the WB **140**.

[0044] The first column portion **100***a* can include an electrically insulating member between the WB **140** and the base plate **105**. For example, the first column portion **100***a* can include an insulating cap **145** that is interposed between the base plate **105** and the WB **140**. The emitter **110**, the insulating cap **145**, and the WB **140** can be stacked in sequence on the base plate **105**, with the insulating cap **145** disposed between the base plate **105** and the WB **140**. The WB **140** can have a shape that generally corresponds to a shape of the adjacent face of the insulating cap **145**. For example, the WB **140** and the insulating cap **145** can have a generally octagonal shape or a rectangular or square shape which can have the corners relieved to provide access to mounting fasteners for mounting the base plate **105** to a mounting surface. The insulating cap **145** can be spaced apart from the base plate **105**, e.g., by mounting lugs, legs, standoffs or the like, and the emitter **110** can be between the insulating cap **145** and the base plate **105**.

[0045] The first conductors **120** can pass through the base plate **105** and the insulating cap **145** to supply power to the WB **140**. Electrical connections between the WB **140** and the emitter **110** can include conductive pins that pass through the insulating cap **145** and are electrically connected to the WB **140**. Electrical connections from the second column portion **100***b* to the emitter **110**, e.g., portions of the conductors **120** and **123** that are on the UHV side of the base plate **105**, can be free of individual or point-to-point wires. Electrical connections from the second column portion **100***b* to the emitter **110** can be free of flexible wires with polymeric insulation in the UHV region of the column **100**.

[0046] An alignment screw **150** or a plurality of the alignment screws **150** can be provided to adjust an alignment, location, or placement of the emitter **110**. For example, an alignment screw **150** or a plurality of the alignment screws **150** can be provided to mechanically align and register the emitter **110** in one or more of X-Y, X-Z, and Y-Z planes, where the X-Y plane is parallel to a major plane of the base plate **105** and the Z axis is normal to the X-Y plane and substantially parallel to the emitted particle beam. Adjusting the alignment screw **150** (by rotating the same) can cause the tip of the alignment screw **150** to move forward or backward, e.g., in the X-Y plane or approximately in the X-Y plane. The flexible power conductor **170** can flex to accommodate movement of the emitter **110**, e.g., lateral movement in the X-Y plane or approximately in the X-Y plane, when the alignment screw **150** moves the emitter **110**.

[0047] The alignment screws **150** can be arranged alongside the emitter **110**, between the base plate **105** and the insulating cap **145**. The emitter **110** can be disposed in a housing **111**, which is a member of the first column portion **100***a*. The housing **111** can be or include an electrically non-conductive and magnetically non-susceptible material. Where such a housing **111** is used, the alignment screw **150**, or plurality thereof, are disposed in contact with the housing **111**, for example by engagement with a threaded support **153** that holds the alignment screw **150**, or plurality thereof, in radial orientation against the housing **111**. In one example, four of the alignment screws **150** are provided as two opposed pairs of the alignment screws **150**. In another example, three of the alignment screws **150** are provided to oppose each other. For example, three of the alignment screws **150** can be arranged with approximately 120 degrees between them.

[0048] One or more of the alignment screws **150** can work in concert with other structures of the first column portion **100***a* to slide and/or tip (or angle) the emitter **110**. For example, the emitter **110** or the housing **111** can have a sloped feature or ramp **114** that, when engaged by the alignment screw **150**, causes the emitter **110** to be moved toward the base plate **105**. The alignment screws **150** can also work in concert with other structures of the first column portion **100***a* to maintain placement of the emitter **110** at a center of the first column portion **100***a*. The alignment screws **150** can also work in concert with other structures of the first column portion **100***a* to maintain electrical contact between the emitter **110** and the base plate **105** where the emitter **110** contacts the base plate **105**, for example using the ramp **114** described above to convert radial force of the alignment screws **150** partially to downward force.

[0049] The second column portion **100***b* can be provided with a detector **190**. The detector **190** can be mounted to an end of the support **125**, i.e., at an end opposite the base plate **105**. The detector **190**, in various examples, detects secondary electrons or ions, and/or backscattered electrons or ions for, e.g., calibration, inspection, metrology, or localized process monitoring. The digital controller **113** can include an analog-to-digital (A-D) converter **113-2** (FIG. **2**A) to convert an analog signal from the detector **190** to a digital signal. The digital controller **113** having the A-D converter **113-1** can be mounted in the HV environment. For example, the digital controller **113** can be mounted to the support **125** or adjacent to the column **100** in the HV environment.

[0050] FIG. **1**B is a schematic cross-sectional view of a modular miniature charged particle beam column apparatus according to an example embodiment. By way of reference, while FIG. **1**A illustrates a structure in which one base plate **105** has, among other things, the emitter **110**, the insulating cap **145**, the WB **140**, the support **125**, and the detector **190**, the modular miniature charged particle beam column apparatus in FIG. **1**B has a base plate **105'** that is extended (relative to the base plate **105** of FIG. **1**A) to provide support for plural sets of the emitter **110**, the support **125**, the detector **190**, and other elements so as to have a plurality of independently-controlled charged particle beam columns coupled to a single base plate **105'**. Thus, the base plate **105'** can have a plurality of first column portions **100***a* coupled to the base plate **105'** and a plurality of the second column portions **100***b* coupled to the base plate **105'**, each second column portion **100***b* corresponding to, and operatively coupled with, one of the first column portions **100***a*. The base plate **105'** can include respective sets of alignment screws **150** (one set for each emitter **110**), wherein each set of alignment screws **150** may comprise 3 alignment screws each set having the alignment screws **150** arranged with approximately 120 degrees between them.

[0051] In FIG. **1**B, an insulating cap **145'** is extended relative to the insulating cap **145** of FIG. **1**A. The insulating cap **145'** in FIG. **1**B is a single insulating cap that corresponds to two emitters **110**. In another example (not shown in FIG. **1**B), two of the insulating caps **145** of FIG. **1**A can be provided such that one insulating cap **145** is provided for each emitter **110**. Thus, a single insulating cap **145'** can be operatively coupled with a plurality of first column portions **100***a*.

[0052] In FIG. **1**B, a wiring board (WB) **140'** is extended relative to the WB **140** of FIG. **1**A. The WB **140'** in FIG. **1**B is a single WB that corresponds to two emitters **110**. In another example (not shown in FIG. **1**B), two of the WB **140** of FIG. **1**A can be provided such that one WB **140** is provided for each emitter **110**. Thus, a single wiring board **140'** can be operatively coupled with a plurality of first column portions **100***a*.

[0053] Although FIG. **1**B shows the base plate **105'** having two sets of the emitter **110**, the support **125**, the detector **190**, and other elements, in another example (not shown), the base plate **105'** can have three or more than three sets of the emitter **110**, the support **125**, the detector **190**, and other elements. In such a case, the insulating cap **145'** and/or the WB **140'** can be extended to correspond to the three or more than three sets of the emitter **110**, the support **125**, the detector **190**, and other elements, or respective insulating caps **145** and/or WB's **140** can be provided. In general, a single base plate **105'** can support a plurality of charged particle beam column devices using one insulating cap **145'** that operatively couples with all the charged particle beam column devices and one wiring board **140'** that operatively couples with all the charged particle beam column devices. Alternately, the single base plate **105'** can be used with a plurality of insulating caps **145** that individually couple with respective charged particle beam column devices and/or a plurality of wiring boards **140** that individually couple with respective charged particle beam column devices.

[0054] FIG. **2**B is a perspective view of an upper portion of the column **100** of FIGS. **1**A and **2**A. The structures shown in FIG. **2**B can be duplicated in a plurality of columns for the apparatus of FIG. **1**B. Power for the emitter **110** can be supplied through the base plate **105**, i.e., from the first side of the base plate **105** to the second side of the base plate **105**, using the first conductors **120**. The first conductors **120** are sealed to the base plate **105** to isolate the UHV environment at the first side of the base plate **105** from the HV environment at the second side of the base plate **105**. The base plate **105** can include holes that penetrate through the base plate **105**, and the first conductors **120** can be disposed through the holes. In an implementation, the first conductors **120** pass through the base plate **105**, are insulated from the base plate **105**, and are sealed to the base plate **105**.

[0055] The first conductors **120** can be at least partially covered with an insulating material. The first conductors **120** can include straight electrically conductive rod portions surrounded by a cylindrical electrical insulator **120***a* formed of a non-conductive, non-volatile, and non-magnetically susceptible insulating material, e.g., a ceramic. The rod portions can be bonded and sealed to the surrounding insulating material. For example, the rod portions can be bonded and sealed to the surrounding insulating material by brazing or by epoxy bonding using a low outgassing epoxy such as TorrSeal.

[0056] The insulator **120***a* can extend through corresponding cylindrical holes in the base plate **105** (refer to the inset in FIG. **2**B). The insulator **120***a* can be bonded and sealed to the base plate **105**. In one example, the insulator **120***a* is bonded and sealed to the base plate **105** by brazing or by epoxy bonding using a low outgassing epoxy, e.g., TorrSeal. In another example, the base plate **105** is or includes titanium, the insulator **120***a* is treated with a metal on a surface of the insulator **120***a* that faces sidewalls of the holes, and the base plate **105** is brazed to the metal-treated insulator **120***a* so as to provide a vacuum seal where the first conductors **120** penetrate the base plate **105**. The metal treatment on the surface of the insulator **120***a* can be applied using any suitable method to coat the surface of the insulator **120***a*. Such methods can include vapor deposition, painting, spraying, and the like. The second conductor **123** can have a same or similar structure as the first conductor **120**, such that the second conductor **123** is at least partially covered with an insulating material that is bonded and sealed to the base plate **105**. FIG. **1**A shows the first conductor **123** being coupled to the second PCB **115_2** by a conductor that passes across the upper surface of the base plate **105** but the second conductor **123** can have a structure like that of the first conductor **120** and extend through the insulating cap **145** to connect to the WB **140**. The first conductor **120** and the second conductor **123** can each connect to the WB **140** by the pin-and-receptacle arrangement described above. The first conductor **120** and the second conductor **123** can each pass through through-holes in the insulating cap **145**. For example, through-holes in the insulating cap **145** may have a size sufficient to allow the first conductor **120** and the second conductor **123** (and their surrounding cylindrical insulators) to pass freely through the insulating cap **145**, e.g., in a non-interference fit.

[0057] FIG. **2**B shows a plurality of supports **153** and corresponding alignment screws **150**. The supports **153** extend between the base plate **105** and the insulating cap **145**. The WB **140** and the insulating cap **145** can be fastened to the supports **153**. The supports **153** include threaded holes (not shown in FIG. **2**B; see threaded holes **152** in FIG. **1**A) through which the alignment screws **150** are deployed in a radial direction of the emitter **110** or the housing **111** (FIG. **1**A) to contact the emitter **110** or the housing **111**. As described above, the supports **153** here are disposed around the emitter **110** to enable four alignment screws **150** to be deployed in pairwise opposition, each support **153** at a 90° angular displacement from each neighboring support **153**. The supports **153**, in this case, are co-located with mounts for the base plate **105** at the relieved corners of the insulating cap **145** and WB **140** to provide access to adjust the alignment screws **150**, and to mount and unmount the base plate **105**. Co-locating the mounts and the alignment screws **150** simplifies structure of the first column portion **100***a*.

[0058] The insulating cap **145** can include a projecting insulating member **145***a* or a plurality of projecting insulating members **145***a* that project through the WB **140**. The projecting insulating member **145***a* can have the shape of a wall. The WB **140** can have slots or openings penetrating therethrough in locations corresponding to the projecting insulating members **145***a*. Each projecting insulating member **145***a* can be disposed relative to conductors in the WB **140**, e.g., conductors that carry high voltages, so as to provide additional electrical isolation between adjacent conductors. The projecting insulating members **145***a* can help to electrically isolate adjacent high-voltage conductors from each other to reduce interactions, e.g., arcing or cross-talk, between the adjacent high-voltage conductors.

[0059] The insulating cap **145** can be made of a non-volatile, electrically non-conductive, and magnetically non-susceptible material. The insulating cap **145** can include, or can be made of, a ceramic material, such as aluminum oxide or another metal oxide. The insulating cap **145** can be a monolithic ceramic structure, or a composite or alloy ceramic structure, and the projecting insulating members **145***a* can be ceramic members that are integral with the monolithic ceramic structure. The projecting insulating members **145***a* can be formed of a same material as the insulating cap **145**. The insulating cap **145** and one or more projecting insulating members **145***a* can be formed as a monolithic unit, e.g., a machined monolithic ceramic unit.

Beam-Control Elements—

[0060] FIG. **1**A schematically illustrates beam-control elements in the second column portion **100***b*. The beam-control elements of the second column portion **100***b* can be held by the support **125**.

[0061] The second column portion **100***b* can include a first control element and a control focusing element. The first control element can form the charged particles into a beam in the second column portion **100***b*. The second control element can be or include an Einzel lens. The second control element can be or include a three-element Einzel lens, with first and third elements being operated at ground voltage while a second (center) element is operated at a high negative voltage to direct a beam onto the workpiece, e.g., a wafer. Either of the first or second control elements can focus the beam to a desired size. The second column portion **100***b* can include beam-control elements that operate at from 5 keV to 50 keV. The beam-control elements can be spaced apart from each other by more than 1 mm. One or more beam-control elements can operate at voltages of approximately 10 kV to 12 kV. In an example, the beam-control elements do not include silicon micro-electromechanical systems (MEMS) elements.

[0062] One or more beam-control elements can be electrostatic elements. The beam-control elements can include one or more electrostatic octupoles for beam deflection. An octupole electromagnetic field can be configured to induce azimuthally-varying third-order deflections to the trajectories of charged particles passing through an **8**N-pole element. A shaped beam, such as a square beam, can formed at the surface of the workpiece by controlling the excitation of the **8**N poles. The **8**N-pole element can be magnetic or electrostatic. Additional examples of beam control are set forth in U.S. Pat. No. 8,242,457, which is incorporated herein in its entirety.

[0063] The support **125** can extend in a direction normal to a sealing surface of the base plate **105** and can have a length sufficient to support all of the beam-control elements. The support **125** can also have the PCB **115** or a plurality of the PCBs **115** affixed thereto. The PCB **115**, e.g., the second PCB **115_2**, can extend to at least partially cover one or more of the beam-control elements. The PCB **115**, e.g., the second PCB **115_2**, can extend to at least partially cover all of the beam-control elements. All signals provided to the beam-control elements can be provided from one or more of the PCBs **115**. All signals provided to the beam-control elements can be provided by the connectors **119** (which can be, e.g., resilient electrical contacts such as pogo pins or the like, as described above) from one or more of the PCBs **115**.

[0064] FIGS. **3**A and **3**B are system diagrams illustrating aspects of a system that includes a plurality of modular miniature charged particle beam columns according to an example embodiment.

[0065] Referring to FIG. **3**A, a system **200** for processing a workpiece can include a plurality of the columns **100**, e.g., arranged in an array **202**. The plurality of columns **100** can all operate on a single workpiece **210**, e.g., a wafer, that is placed in the system **200**. For example, as shown in FIG. **3**A, nine columns **100** can be arranged in a 3×3 array **202** to operate on the workpiece **210**, which may be, e.g., a 200 mm wafer. The columns **100** in the array **202** can operate in concert, e.g., write in parallel, on the same workpiece **210**. The system **200** can include a chuck **206** upon which the workpiece **210** is mounted while the workpiece **210** is operated on in the system **200**. The system can include a workpiece positioning system **208** that moves the chuck **206** relative to the array **202**.

[0066] Referring to FIG. **3**B, a cluster tool **250** can include a plurality of modules each including the system **200**, each of said systems **200** including a plurality of the columns **100** and each operating on a respective workpiece **210**. The cluster tool **250** can include one or more of a workpiece handling system **252**, a workpiece loading/unloading system **254**, and one or more workpiece transport systems **256**. A plurality of the columns **100** can be provided for a processing chamber of each system **200**. As such, the cluster tool **250** can include a plurality of the processing chambers each including a plurality of the columns **100**. The modular nature of the small charged particle devices described herein enables use of multiple such devices in a processing system because the devices can be easily installed and removed, with electrical connections being passively established when the device is inserted into the processing system. Such devices can also be transported between a test or calibration system and a processing system because all controls for each device are local to the device and can be transported with the device between systems. For example, the PCBs **115**, which have memory circuits, can store calibration information developed for a device in a calibration system, for use in a production system.

[0067] FIG. **4** illustrates a method of aligning an emitter **110** according to an example embodiment. The method **400** includes an operation **410** of installing or replacing the emitter **110** in the column **100** to place the emitter **110** in an operating position.

[0068] The method can include, after the emitter **110** is installed, an operation **420** of optically aligning the emitter **110** can be performed. Optically aligning the emitter **110** can include examining a tip of the emitter **110** under magnification, e.g., using a microscope, and moving the emitter **110** using one or more alignment screws **150**, as described above. The operation **420** can be performed "cold," i.e., in a state in which electrical power is not provided to the emitter **110** and/or the column **100**, relying purely on optical observation of the emitter **110** position to perform the alignment. In one example, during the cold alignment, the column **100** is not installed in a vacuum chamber or processing chamber. The cold state can be a state in which the column **100** is at room temperature, e.g., 25° C., and/or atmospheric pressure, e.g., 1 atm or 760 Torr. In another example, the operation **420** can be performed with the column **100** mounted in an alignment jig or test system, e.g., a test chamber.

[0069] The method **400** can include, after the emitter **110** is installed, an operation **430** of active alignment of the emitter **110**. The active alignment of the emitter **110** can include providing power and control signals to the emitter **110** with the emitter **110** in a vacuum environment, and observing charged particles emitted from the emitter **110** while the emitter **110** is operating. This "hot" (i.e., powered) alignment can include placing the column **100** in a production-like environment. The production-like environment can be a test, calibration, or alignment chamber in which vacuum levels and/or temperatures are the same as or similar to an exemplary or intended production environment of a processing chamber.

[0070] In operation **430**, the active alignment of the emitter **110** can include evaluating an attribute of the beam, such as a beam current, developed by charged particles emitted from the emitter **110**. Adjustments to the column **100** can be made while evaluating the attribute of the beam. For example, the beam current can be measured while moving the emitter **110** using one or more alignment screws **150**. The operation **430** can include using a suitable tool or actuator to manipulate the one or more alignment screws **150** in the vacuum environment during the hot alignment.

[0071] The method **400** can include an operation **440** of storing information relating to the attribute of the beam that is evaluated in operation **430**. For example, a memory, e.g., a digital nonvolatile memory, can be coupled to the column **100** (e.g., provided on one or more of the PCBs **115** in the second column portion **100*b***) and the information relating to the attribute of the beam can be stored in the memory. The information relating to the attribute of the beam can thus be stored local to the column **100** so as to be portable with the column **100** or on-board the column **100**.

[0072] The operation **430** of hot alignment can be performed without performing the operation **420** of cold alignment.

[0073] FIG. **5** illustrates a method of preparing a column **100** according to an example embodiment. The method **500** includes an operation **510** of placing the column **100** in an active state, in which power and control signals are provided. The operation **510** can be performed with the column **100** mounted in a first system. The first system can be a test, calibration, or alignment chamber in which vacuum levels and/or temperatures are the same as or similar to an exemplary or intended production environment of a processing chamber. The method **500** can be a calibration method.

[0074] The method **500** can include, after placing the column **100** in the active state (e.g., powered-up and in a test chamber at operating vacuum levels and temperatures), an operation **520** of calibrating the column **100** in the first system. The operation **520** can include providing a digital signal to the column **100**, converting the digital signal to an analog signal using a D-A converter that is coupled to the column **100** (e.g., mounted, in the HV environment, to the support **125** or adjacent to the column **100** in the HV environment), and applying the analog signal to an beam-control element, such a lens, deflector, or the like, of the column **100**. The operation **520** can include identifying an optimal signal, e.g., a value of an optimal digital signal or a corresponding optimal analog signal, for one or more beam-control elements of the column **100**. By calibrating the column **100** using a D-A converter that is coupled to the column, better-optimized initial conditions may be achieved by a modular implementation that includes the D-A converter coupled to a beam-control element that it controls.

[0075] The method **500** can include an operation **530** of storing calibration information for the column **100**. The optimal signal from operation **520** can be stored as a calibration setting. The calibration information can be stored as digital data in a memory. The calibration information can be stored off the column **100** or on-board the column **100**. The calibration information can be stored in a memory that is a non-volatile digital memory mounted on or deployed in one or more of the PCBs **115**, such that the stored calibration information is stored on-board the column **100**.

[0076] The method **500** can include an operation **540** of removing the column **100** from the first system and installing the column **100** in a second system. The second system can be a production system. The first system can include provisions to mount a single column **100** and the second system can include provisions to mount a plurality of columns **100**, e.g., in an array.

[0077] The method **500** can include an operation **550** of operating the column **100** in the second system, the operating in the second system including providing a digital signal to the D-A converter coupled to the column **100**, and applying the generated analog signal to the beam-control element of the charged particle beam device while the column **100** is installed in the second system. For example, the stored calibration information from operation **540** (which can be stored in a memory mounted on or deployed in one or more of the PCBs **115**) can be read as the digital signal that is then provided to the D-A converter.

[0078] The methods **400** and **500** described above can be employed for each of a plurality of the columns **100**, which thus can respectively be pre-aligned and pre-calibrated. In a production environment, e.g., a fab or the like, a system employing the columns **100** can be maintained with a greater operation up-time by replacing a used column **100** with a fresh, pre-aligned and pre-calibrated column **100**.

[0079] As described above, according to an example embodiment, a charged particle beam column is a small, modular device that allows for a relatively close spacing of columns to enable multiple columns to operate on a same workpiece, and enables operation in a high-throughput system such as a production system. Whereas a research and development facility may employ a single, relatively large column and may be used for iterative or one-off product development that is relatively undemanding in terms of throughput, a production environment imposes demands for high throughput and high up-time. A charged particle beam column according to an example embodiment can enable high workpiece throughput by operating multiple columns on a same workpiece, and can enable high up-time by simplifying column startup procedures and reducing repair time.

[0080] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the present disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

We claim:

1. A charged particle beam device, comprising:
a first column portion, comprising:
an emitter; and
a mechanical alignment structure coupled to the emitter;
a second column portion connected to the first column portion; and
a passively connectable power coupling coupled to the emitter.

2. The charged particle beam device of claim **1**, wherein the second column portion and the first column portion are coupled at a sealed interface.

3. The charged particle beam device of claim **2**, wherein the sealed interface comprises a thermally conductive plate.

4. The charged particle beam device of claim **2**, wherein the passively connectable power coupling comprises a plurality of electrical conductors disposed through the sealed interface.

5. The charged particle beam device of claim **4**, wherein the sealed interface comprises a plate, each of the electrical conductors is disposed through a hole in the plate, each of the electrical conductors is at least partially surrounded by an insulator, and the insulator is bonded to the plate within the respective hole.

6. The charged particle beam device of claim **1**, wherein the mechanical alignment structure comprises a plurality of opposed screws.

7. The charged particle beam device of claim **1**, further comprising a digital controller coupled to the second column portion, the digital controller comprises a D-A converter.

8. A charged particle beam device, comprising:
a first column portion, comprising:
an emitter; and
a mechanical alignment structure coupled to the emitter;
a second column portion connected to the first column portion and comprising a control assembly and a digital controller attached to the control assembly; and
a passively connectable power coupling coupled to the emitter.

9. The charged particle beam device of claim **8**, wherein the second column portion and the first column portion are coupled at a sealed interface comprising a thermally conductive plate, and a thermal conduit thermally couples the digital controller to the thermally conductive plate.

10. The charged particle beam device of claim **8**, wherein the control assembly comprises a plurality of beam-control elements, and the digital controller is electrically connected to the beam-control elements.

11. The charged particle beam device of claim **8**, further comprising a D-A converter on the second column portion, an A-D converter on the second column portion, or both.

12. The charged particle beam device of claim **8**, further comprising a detector on the second column portion and an A-D converter coupled to the detector to receive an analog signal from the detector.

13. The charged particle beam device of claim **8**, wherein the digital controller comprises a memory to digitally store calibration information, identification information, test information, operation information, or any combination thereof.

14. The charged particle beam device of claim **10**, wherein the beam-control elements are analog elements and the digital controller comprises a D-A converter electrically coupled to the beam-control elements.

15. A charged particle beam device, comprising:
a first column portion, comprising:
an emitter; and
a mechanical alignment structure coupled to the emitter;
a second column portion connected to the first column portion and comprising a control assembly and a digital controller attached to the control assembly;
a thermal conduit coupled to the digital controller; and
a passively connectable power coupling coupled to the emitter.

16. The charged particle beam device of claim **15**, wherein:
the second column portion and the first column portion are coupled at a sealed interface,
the first column portion comprises a plate that forms the sealed interface, the emitter is a first emitter and is coupled to the plate, and
at least a second emitter is coupled to the plate.

17. The charged particle beam device of claim **16**, wherein the passively connectable power coupling comprises a plurality of electrical conductors disposed through the sealed interface and each electrical conductor is separated from the sealed interface by an insulator having a metal-treated surface.

18. The charged particle beam device of claim **15**, wherein the digital controller comprises a D-A converter.

19. The charged particle beam device of claim **18**, wherein the digital controller comprises a circuit board attached to the control assembly.

20. The charged particle beam device of claim **15**, further comprising a wiring board coupling the passively connectable power coupling to the emitter.

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