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(54) **ADDITIVE MANUFACTURING OF SILICON COMPONENTS**

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B33Y 30/00	(2015.01)

(52) **U.S. Cl.**
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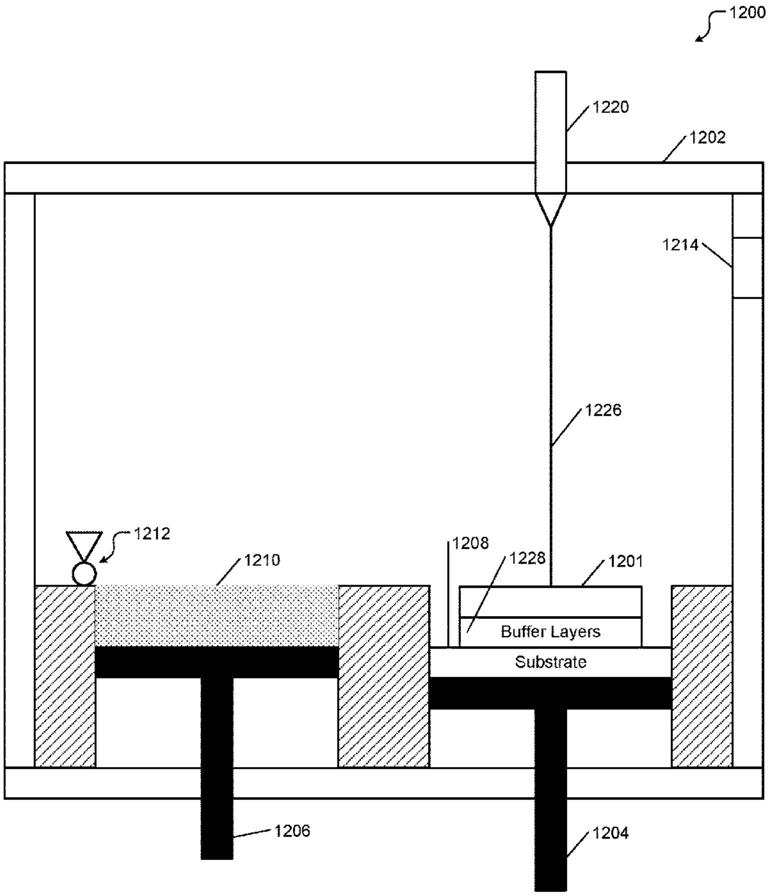
(57) **ABSTRACT**

A method of performing 3D printing of a silicon component includes adding powdered silicon to a 3D printing tool. For each the powdered silicon, forming a layer of the powder bed to a pre-determined thickness, directing a high-powered beam in a pre-determined pattern into the powder-bed to melt the powdered silicon. After no further layers are needed, the silicon component is cooled at a pre-determined temperature ramp-down rate. In a fully dense printing method, buffer layers of silicon are initially printed on a steel substrate, and then layers of silicon for the actual component are printed on top of the buffer layers using a double printing method. In a fully dense and crack free printing method, one or more heaters and thermal insulation are used to minimize temperature gradient during Si printing, in-situ annealing, and cooling.



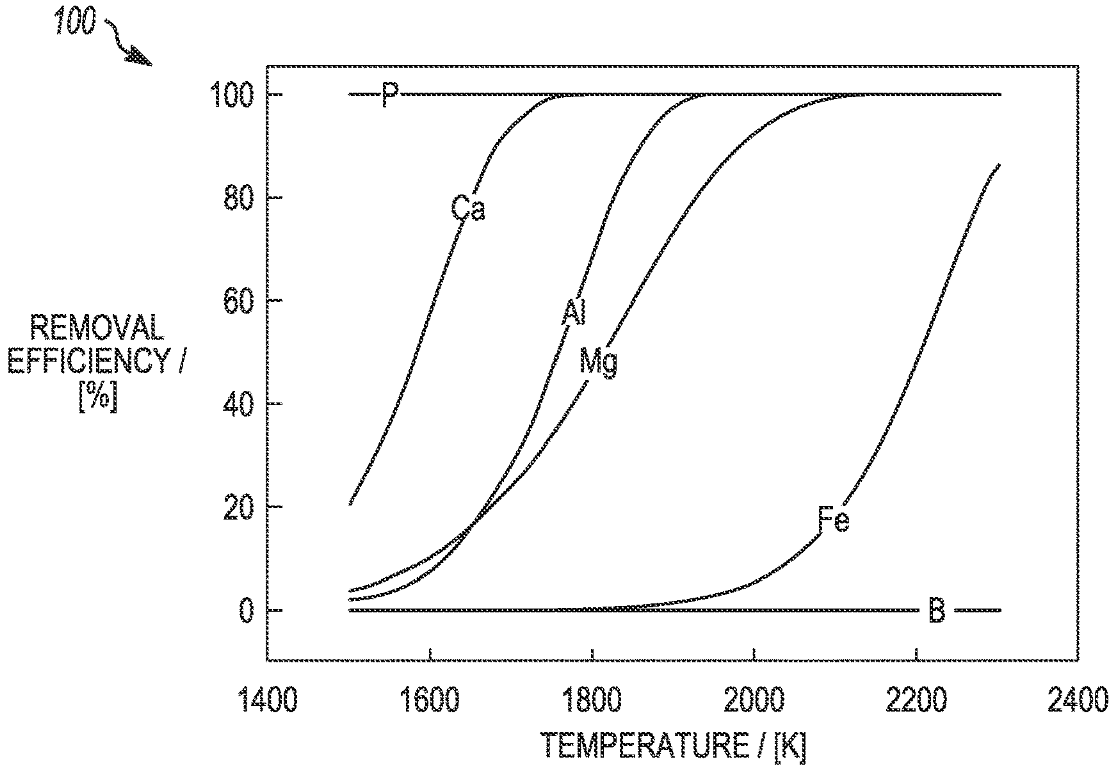

100
REMOVAL EFFICIENCY / [%]
100
80
60
40
20
0
1400
1600
1800
2000
2200
2400
TEMPERATURE / [K]
P
Ca
Al
Mg
Fe
B

FIG. 1A

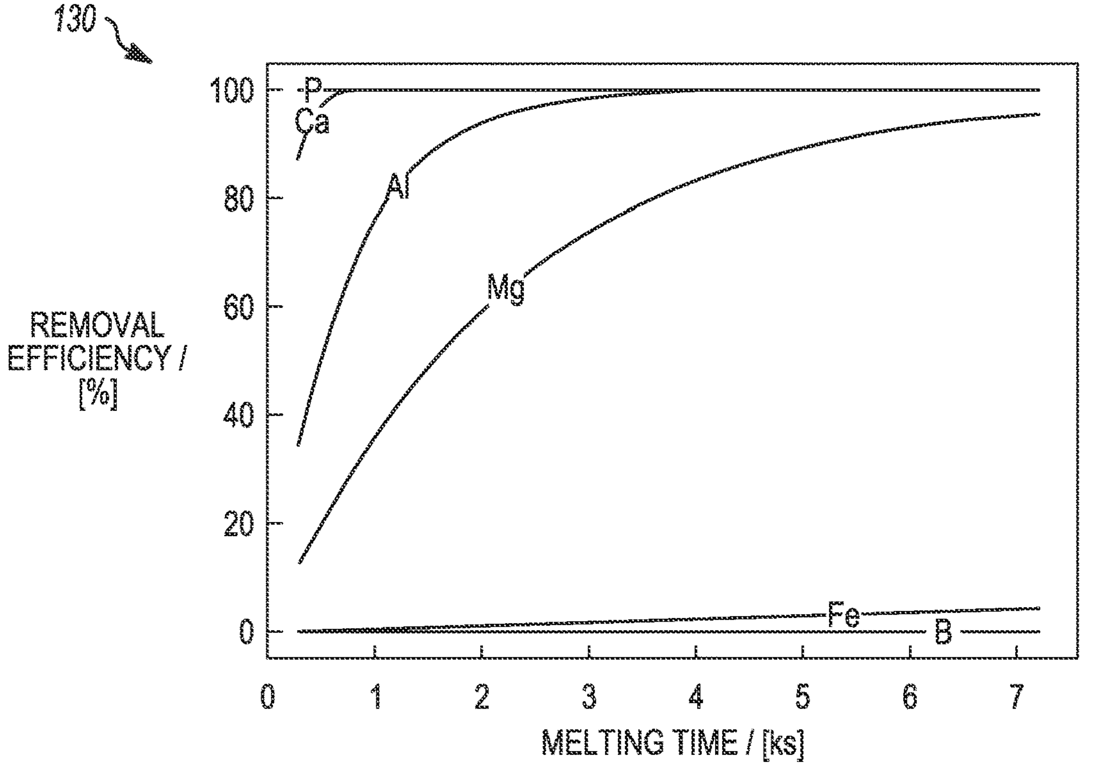

130
REMOVAL EFFICIENCY / [%]
100
80
60
40
20
0
0
1
2
3
4
5
6
7
MELTING TIME / [ks]
P
Ca
Al
Mg
Fe
B

FIG. 1B

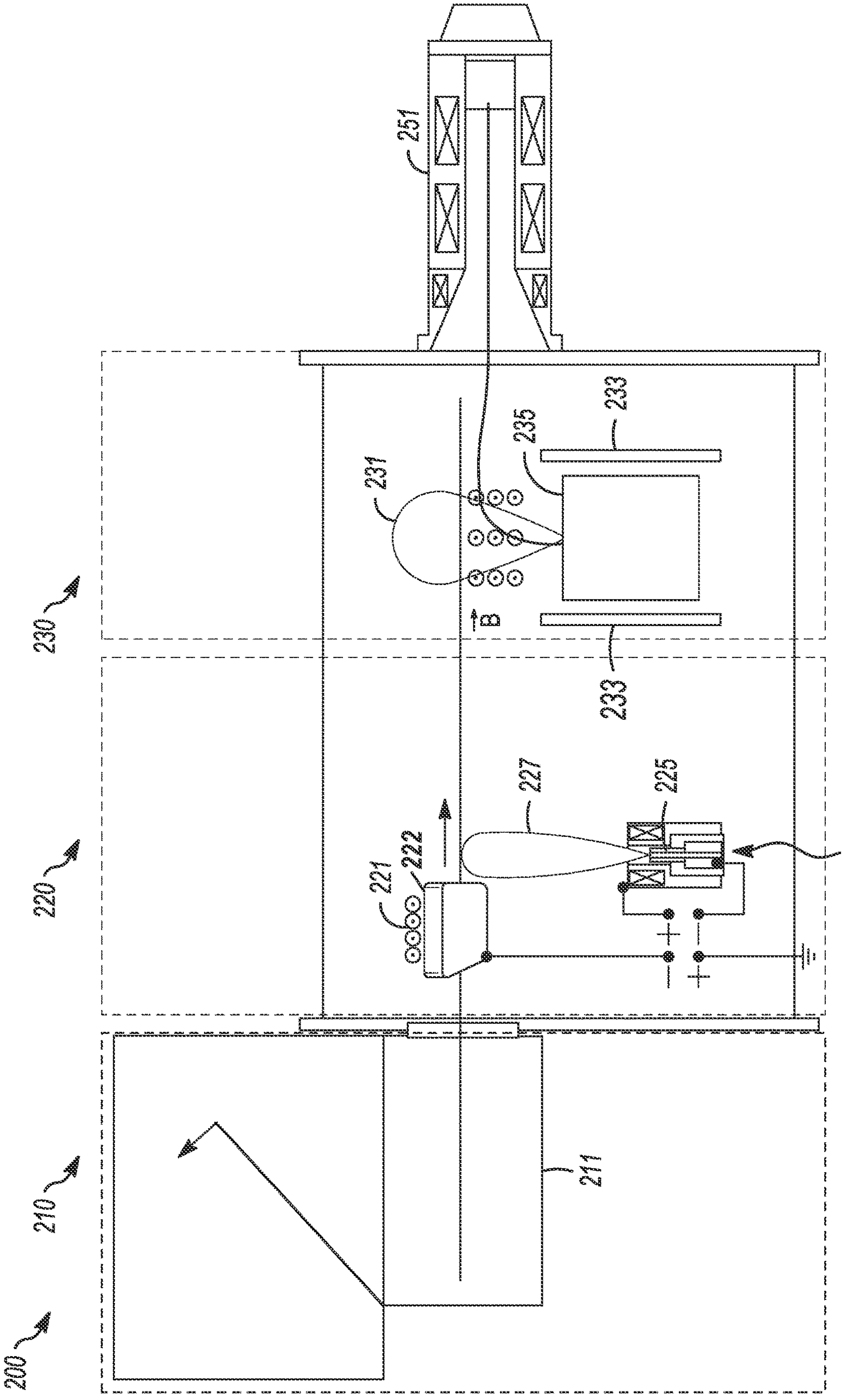


FIG. 2

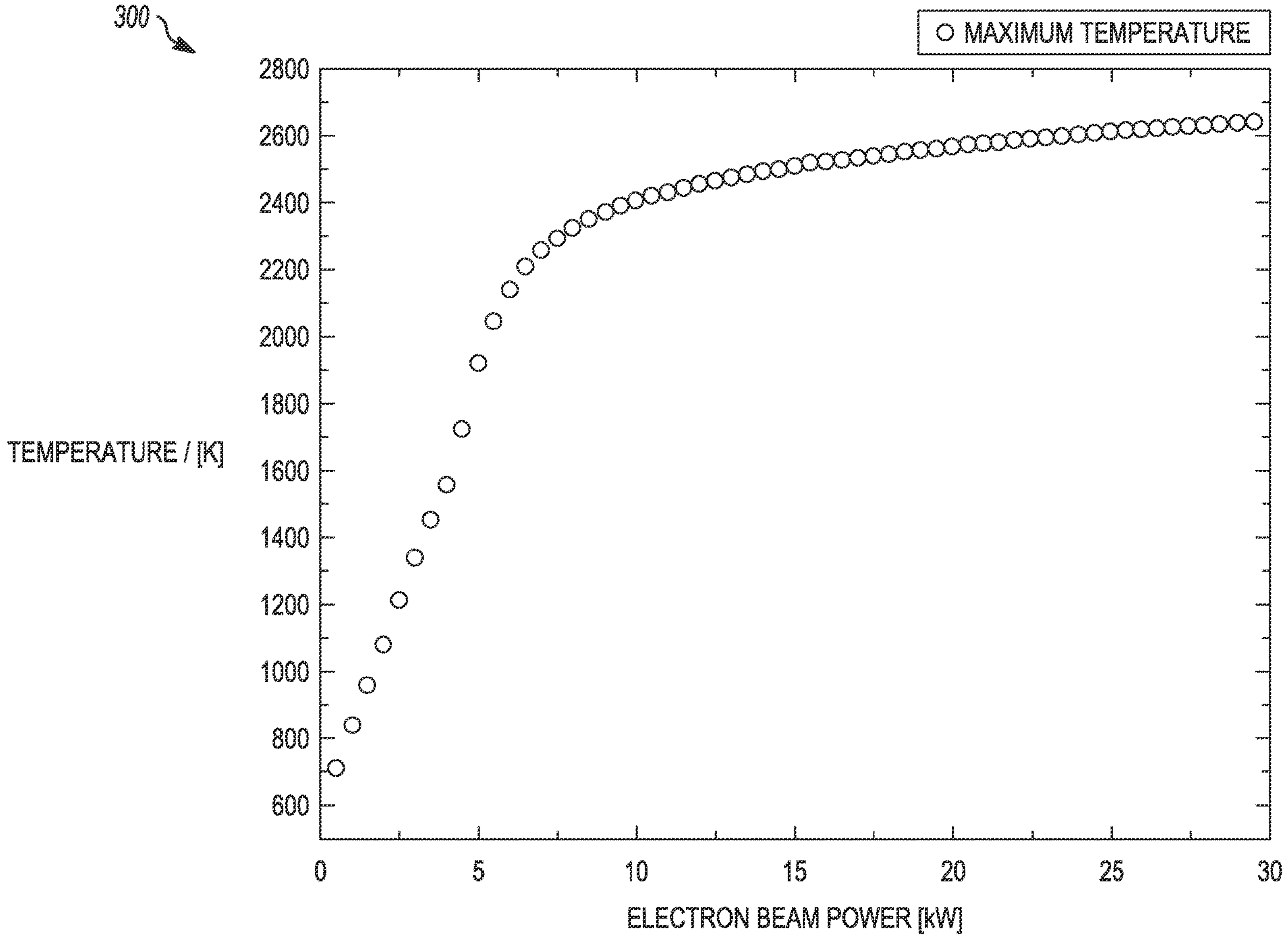

300
MAXIMUM TEMPERATURE
TEMPERATURE / [K]
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
0
5
10
15
20
25
30
ELECTRON BEAM POWER [kW]

FIG. 3

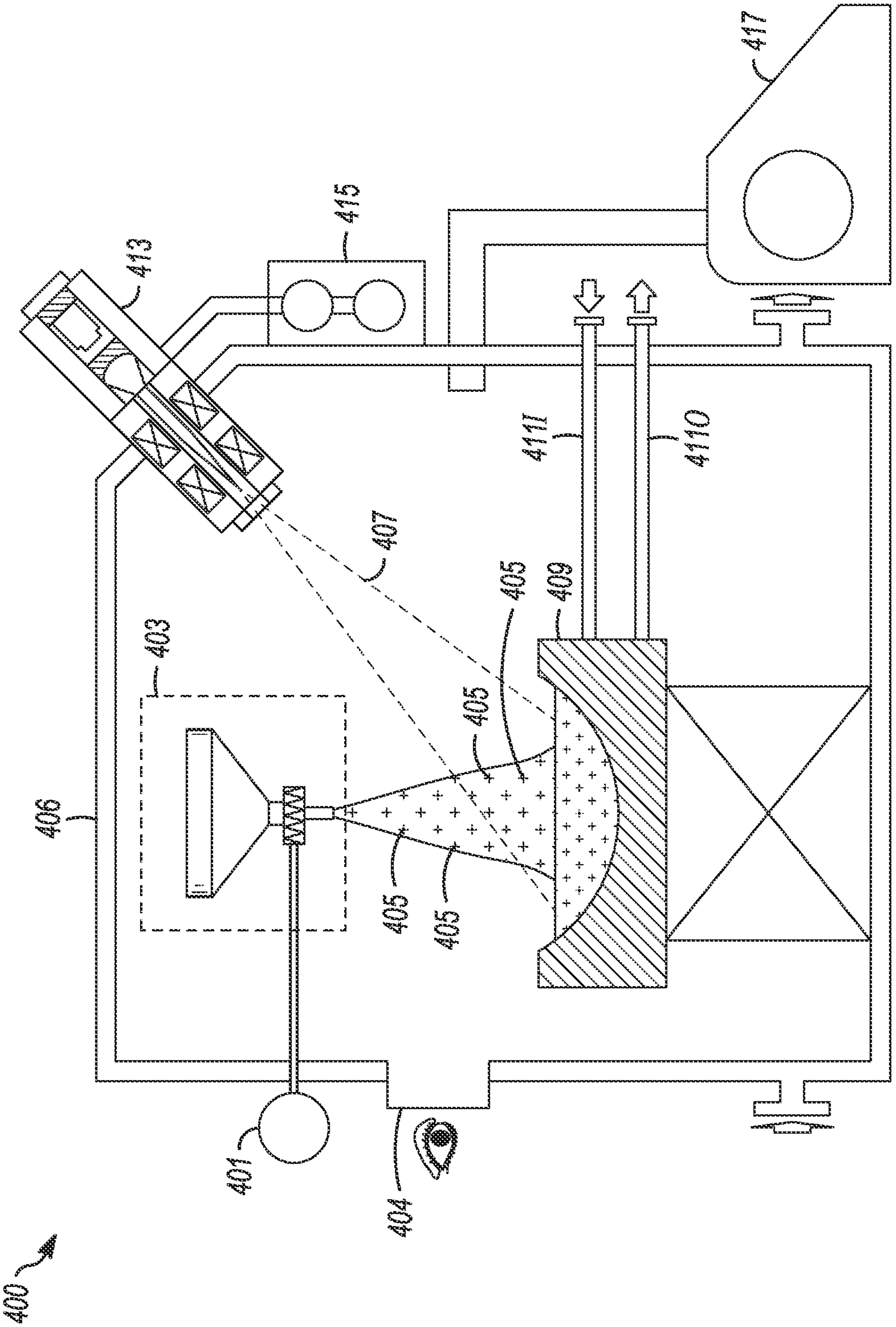

400
401
403
404
405
405
405
405
405
406
407
409
4111
4110
413
415
417

FIG. 4

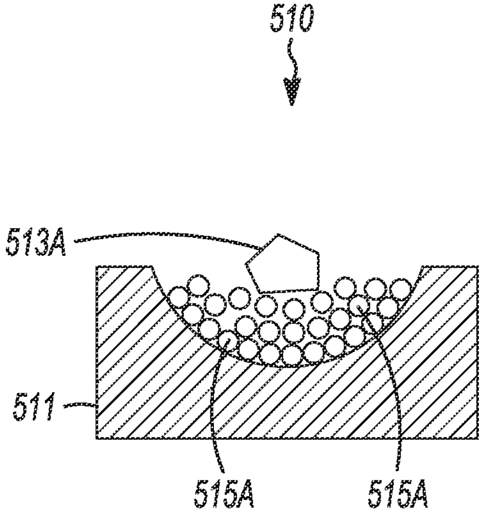


FIG. 5A

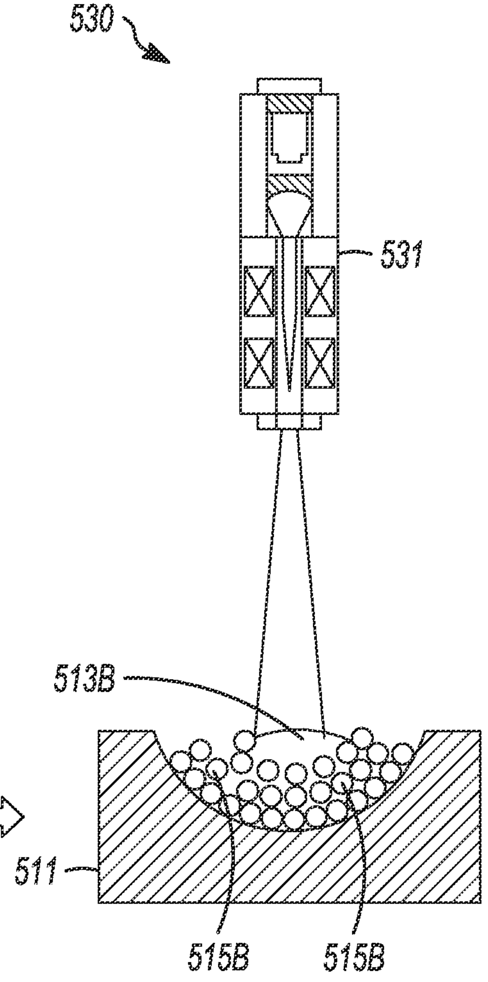


FIG. 5B

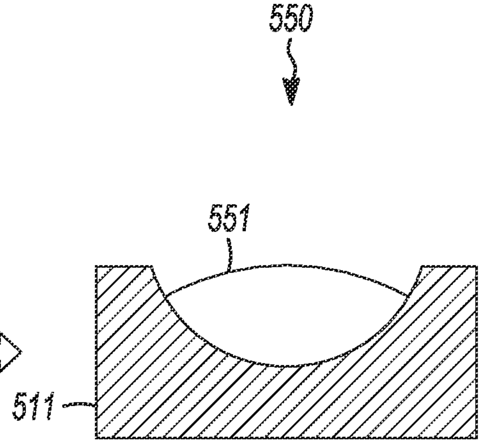


FIG. 5C

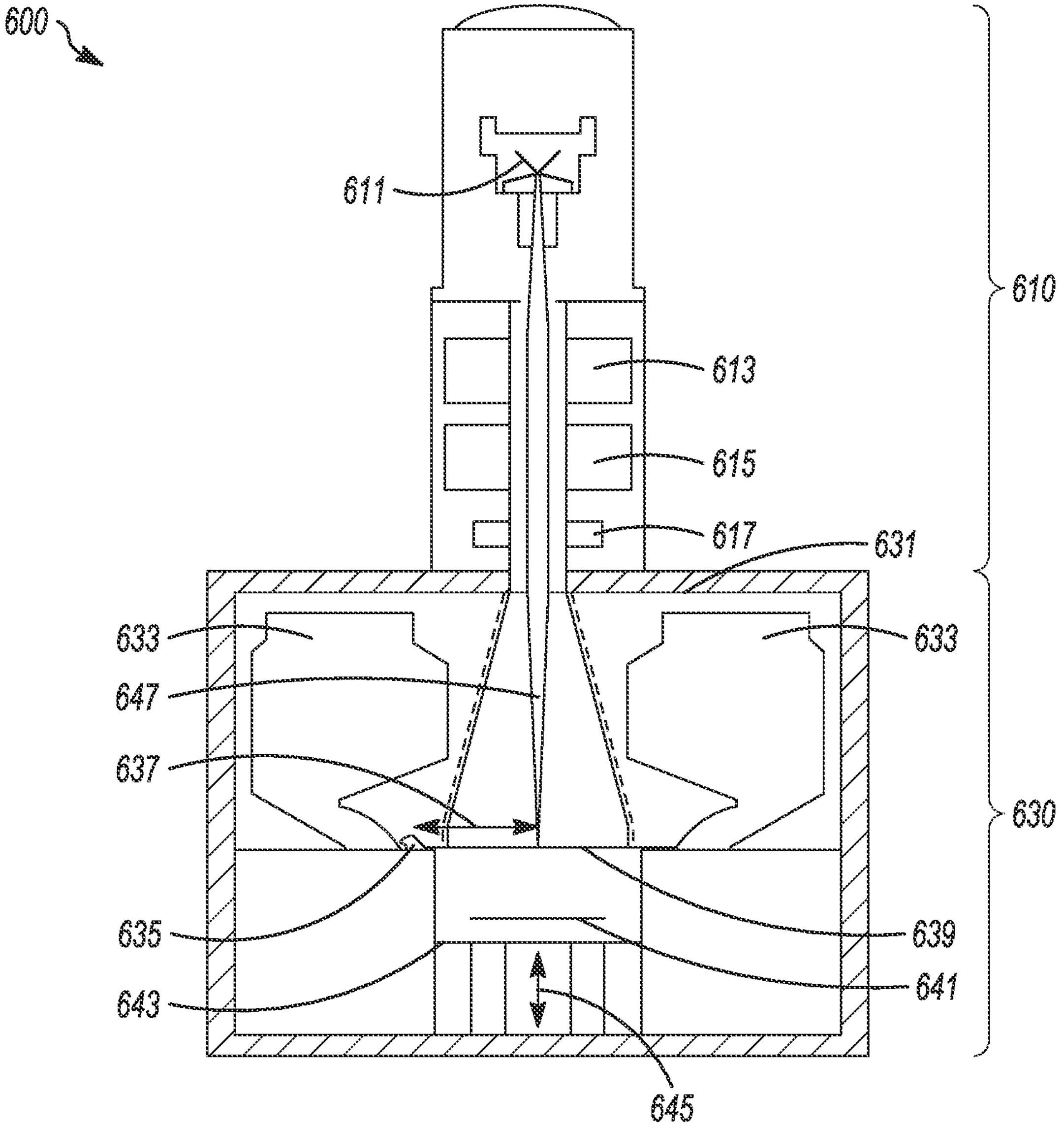

600
611
610
613
615
617
631
633
633
647
637
630
635
639
641
643
645

FIG. 6

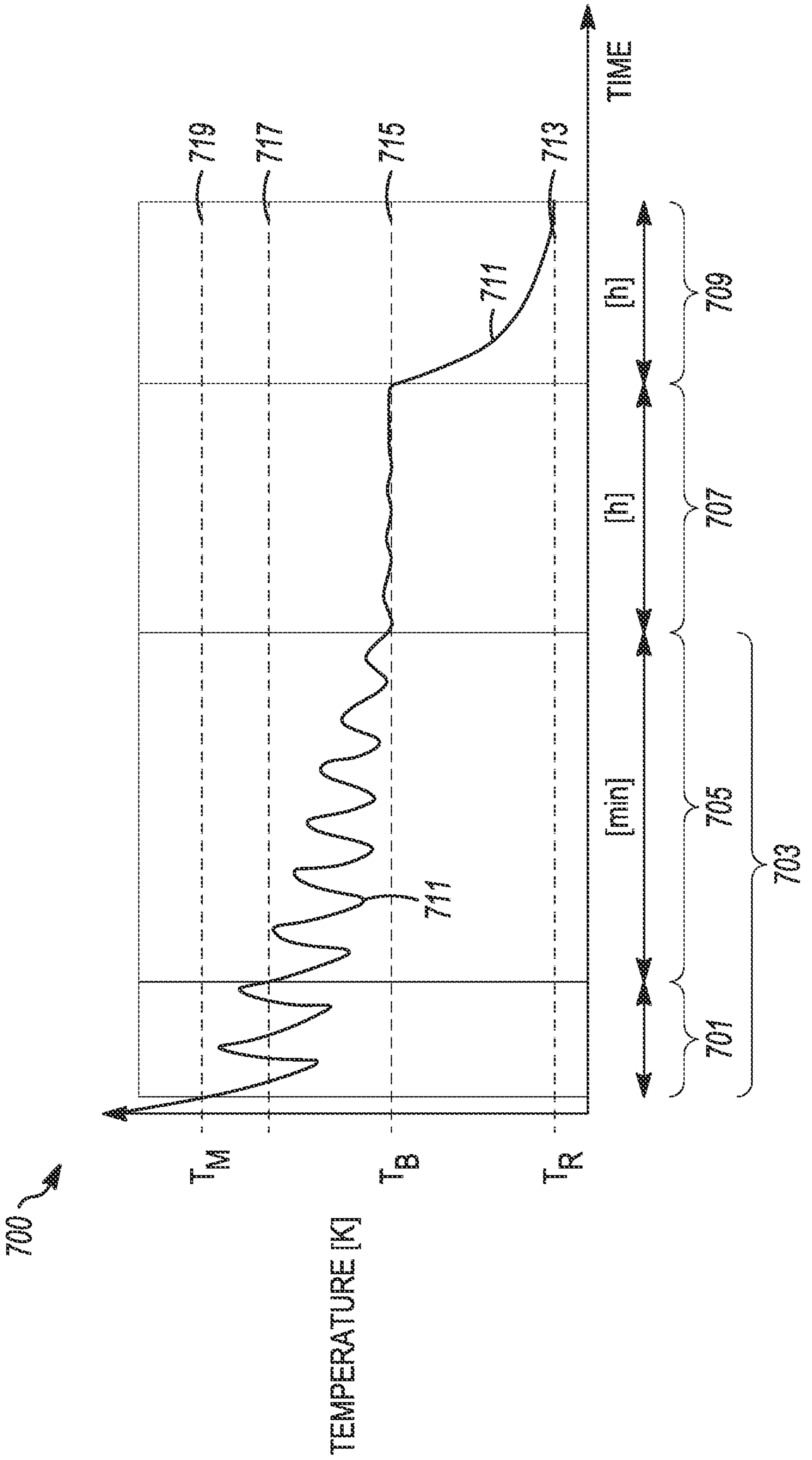

700
TEMPERATURE [K]
T_M
T_B
T_R
TIME
719
717
715
713
711
711
[min]
[h]
[h]
701
705
707
709
703

FIG. 7

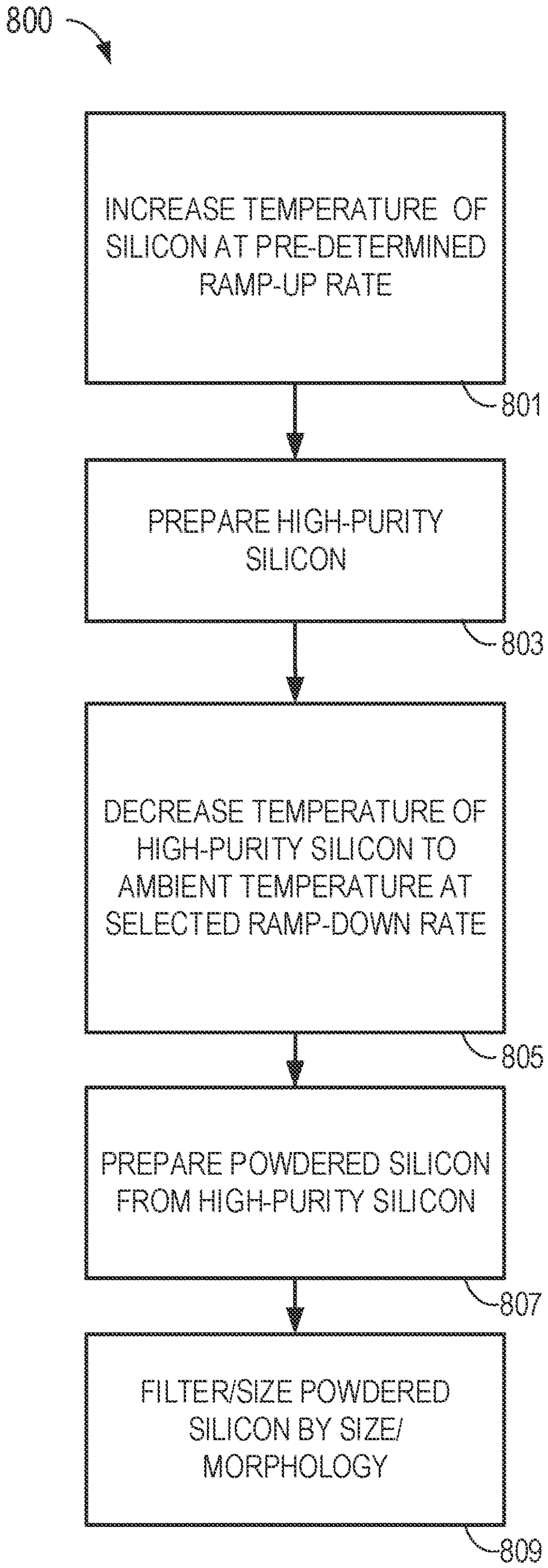

800
INCREASE TEMPERATURE OF SILICON AT PRE-DETERMINED RAMP-UP RATE
801
PREPARE HIGH-PURITY SILICON
803
DECREASE TEMPERATURE OF HIGH-PURITY SILICON TO AMBIENT TEMPERATURE AT SELECTED RAMP-DOWN RATE
805
PREPARE POWDERED SILICON FROM HIGH-PURITY SILICON
807
FILTER/SIZE POWDERED SILICON BY SIZE/ MORPHOLOGY
809

FIG. 8A

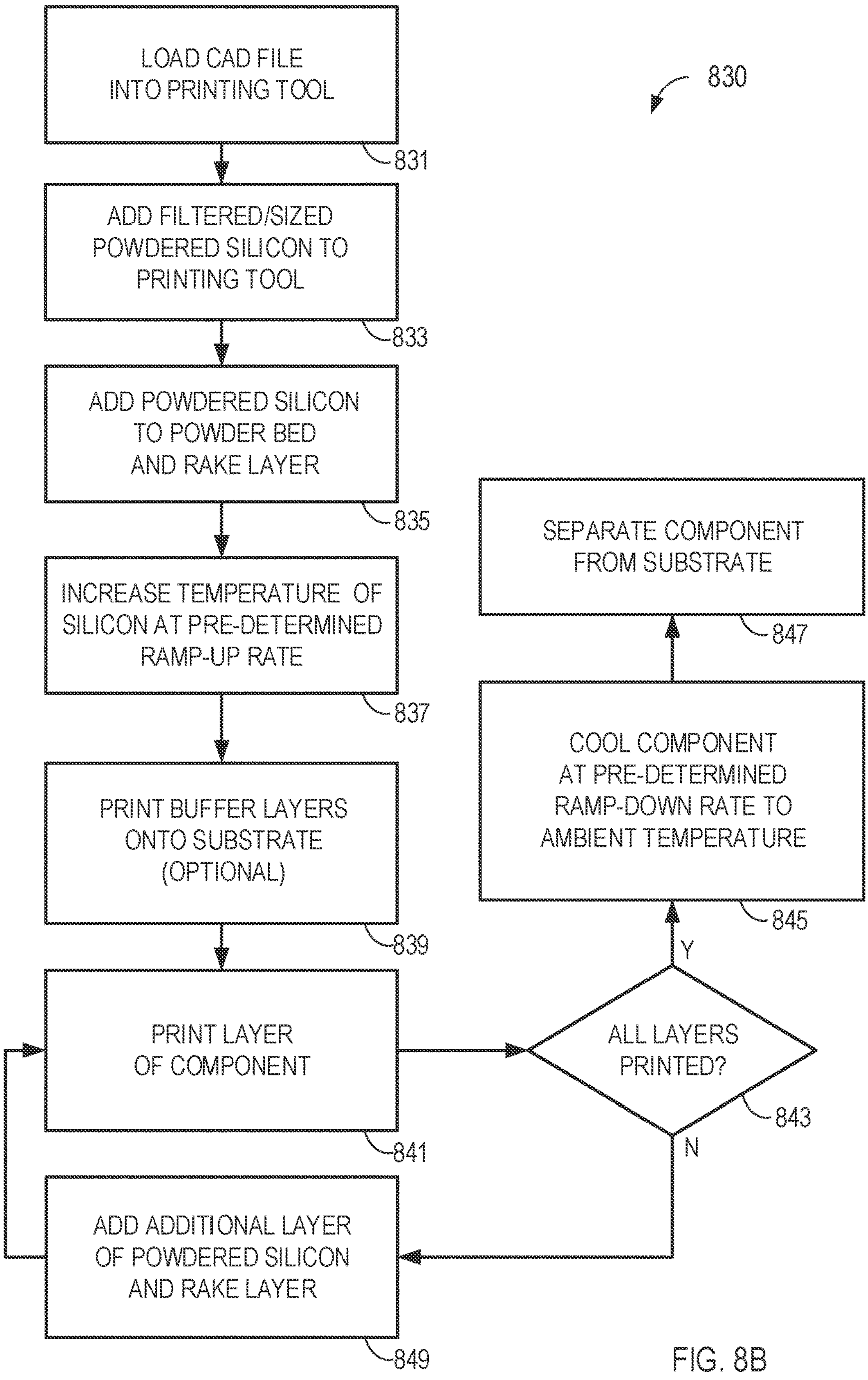

830
LOAD CAD FILE INTO PRINTING TOOL
831
ADD FILTERED/SIZED POWDERED SILICON TO PRINTING TOOL
833
ADD POWDERED SILICON TO POWDER BED AND RAKE LAYER
835
INCREASE TEMPERATURE OF SILICON AT PRE-DETERMINED RAMP-UP RATE
837
PRINT BUFFER LAYERS ONTO SUBSTRATE (OPTIONAL)
839
PRINT LAYER OF COMPONENT
841
ALL LAYERS PRINTED?
843
Y
N
COOL COMPONENT AT PRE-DETERMINED RAMP-DOWN RATE TO AMBIENT TEMPERATURE
845
SEPARATE COMPONENT FROM SUBSTRATE
847
ADD ADDITIONAL LAYER OF POWDERED SILICON AND RAKE LAYER
849

FIG. 8B

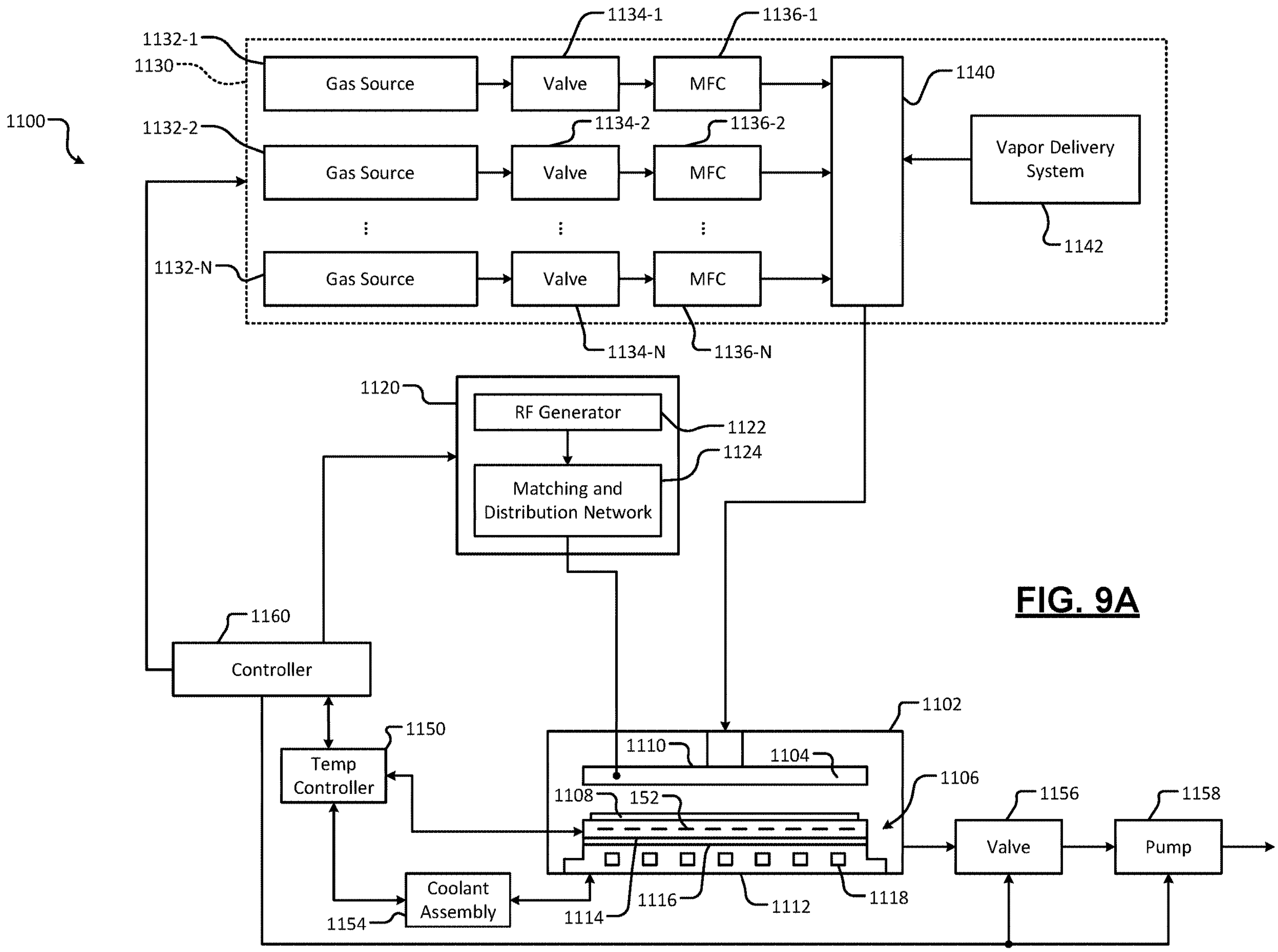

1100
1132-1
1130
1132-2
1132-N
Gas Source
Gas Source
Gas Source
1134-1
1134-2
1134-N
Valve
Valve
Valve
1136-1
1136-2
1136-N
MFC
MFC
MFC
1140
Vapor Delivery System
1142
1120
RF Generator
1122
Matching and Distribution Network
1124
1160
Controller
1150
Temp Controller
1154
Coolant Assembly
1102
1110
1104
1108
152
1106
1114
1116
1112
1118
1156
Valve
1158
Pump

FIG. 9A

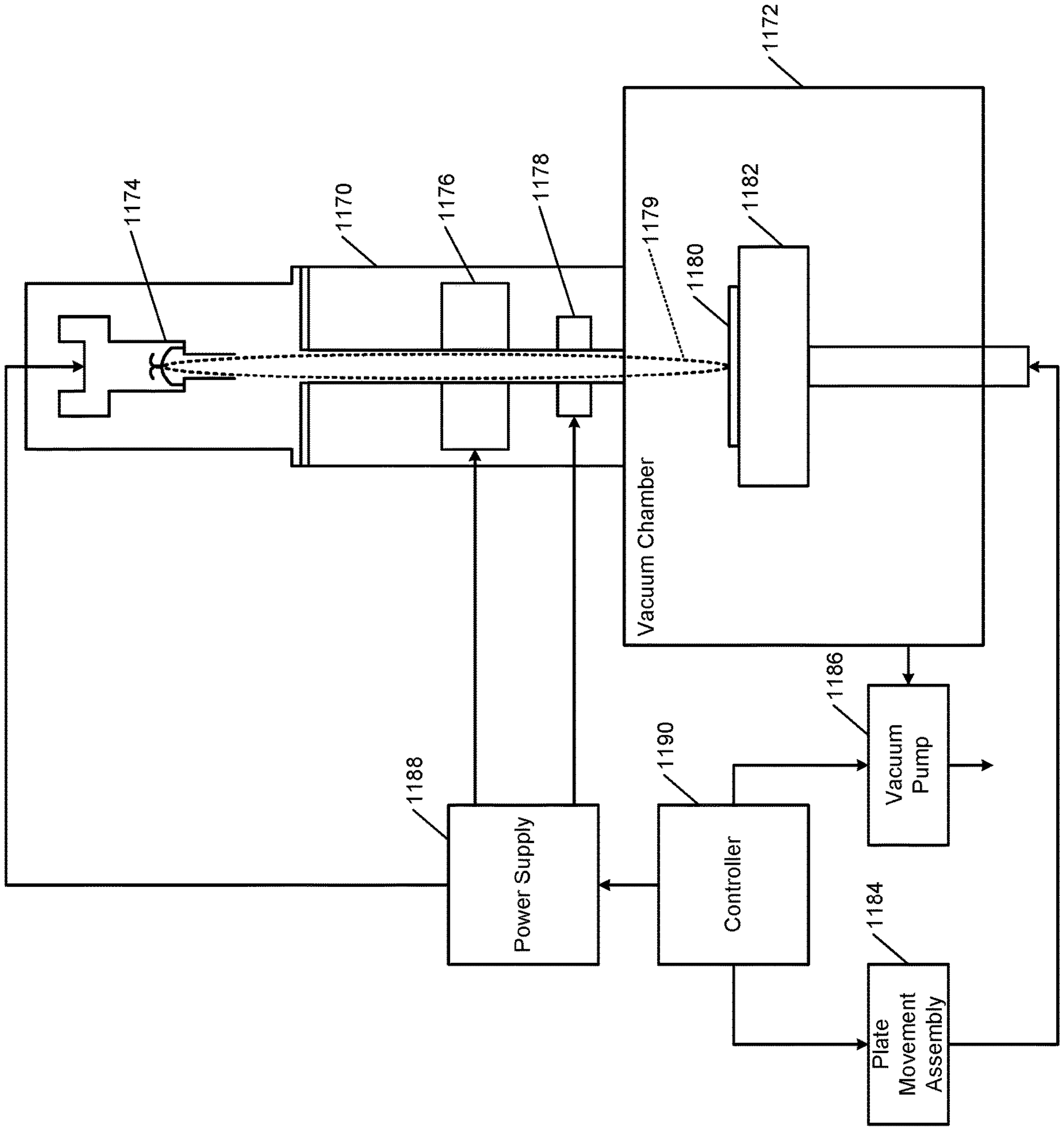

1174
1170
1176
1178
1179
1180
1182
1172
Vacuum Chamber
1186
Vacuum Pump
1190
Controller
1188
Power Supply
1184
Plate Movement Assembly

FIG. 9B

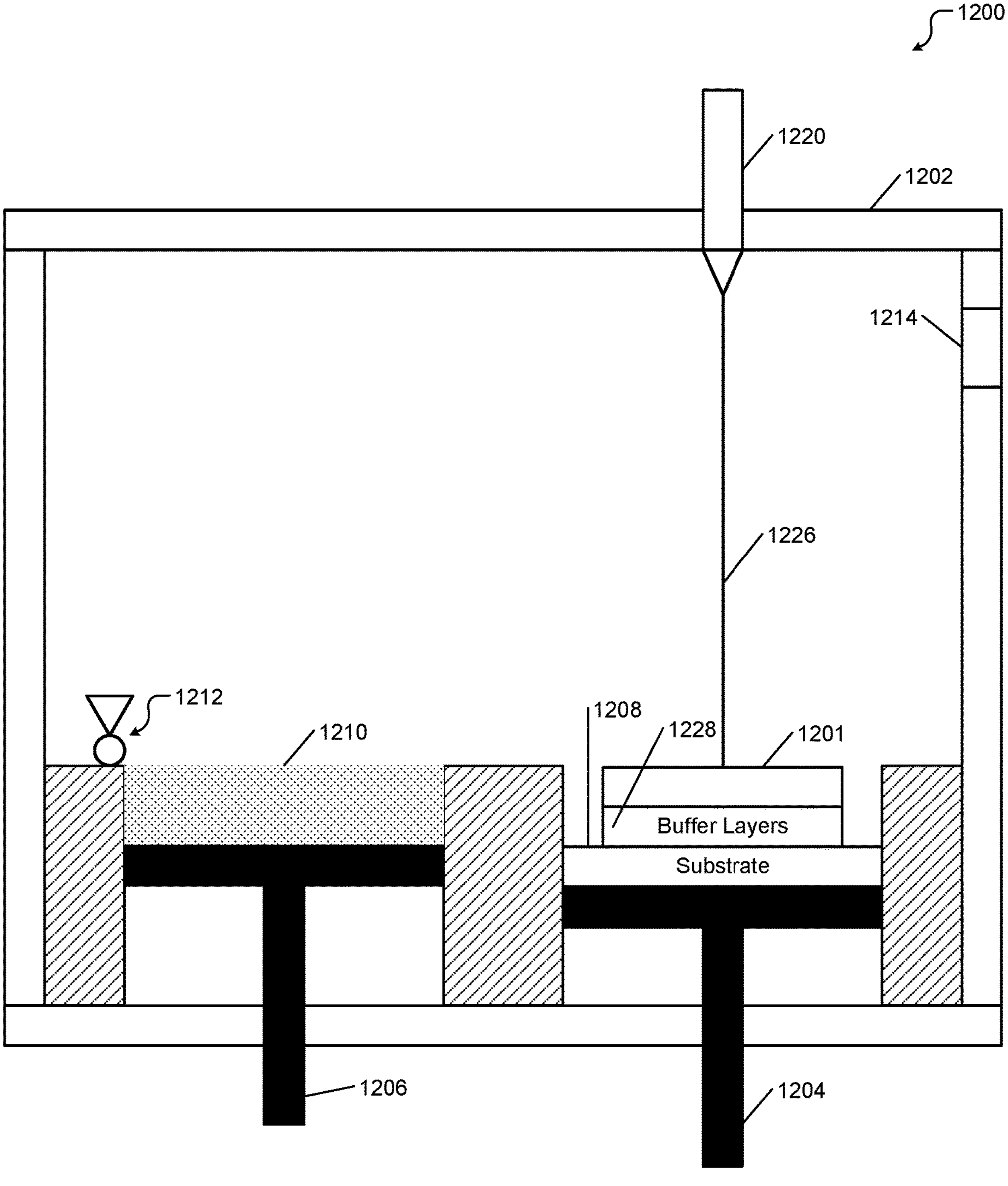

1200
1220
1202
1214
1226
1212
1210
1208
1228
1201
Buffer Layers
Substrate
1206
1204

FIG. 10A

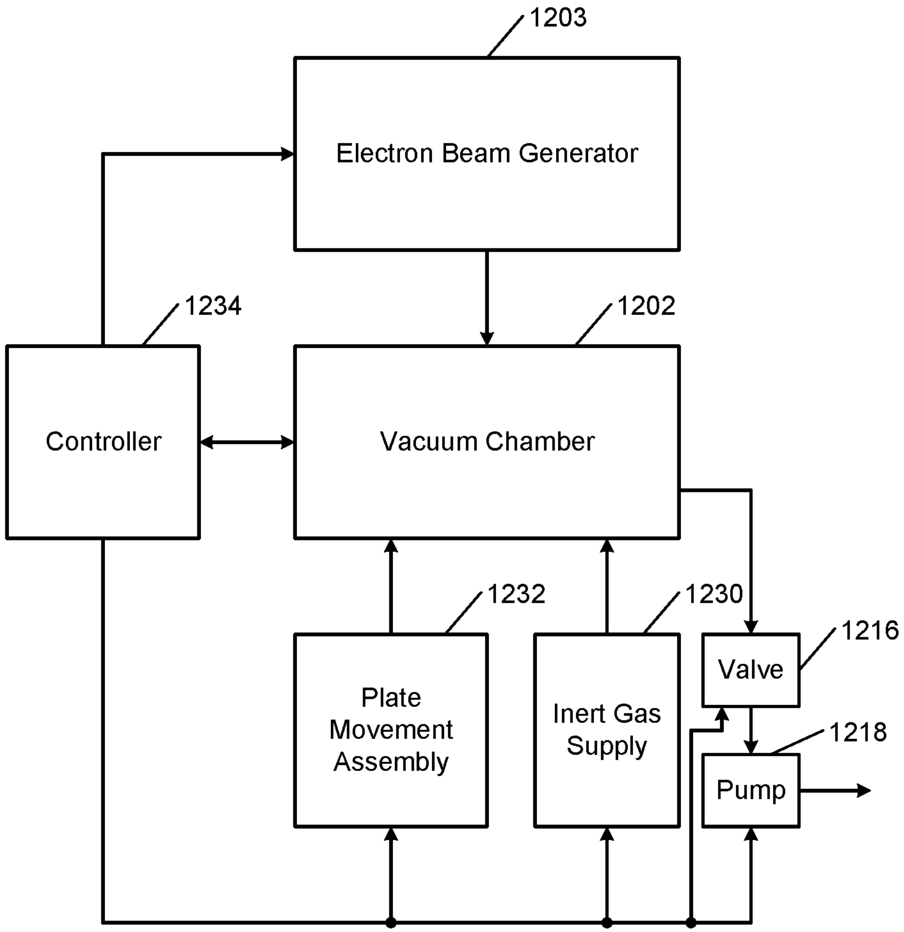


FIG. 10B

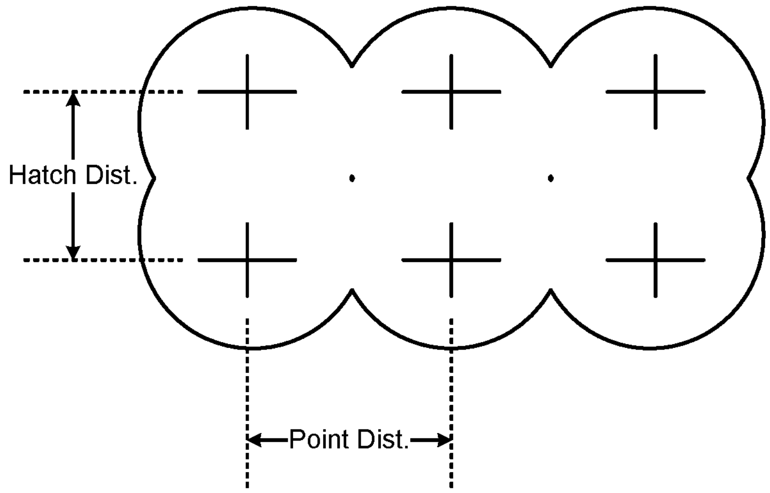


FIG. 10C

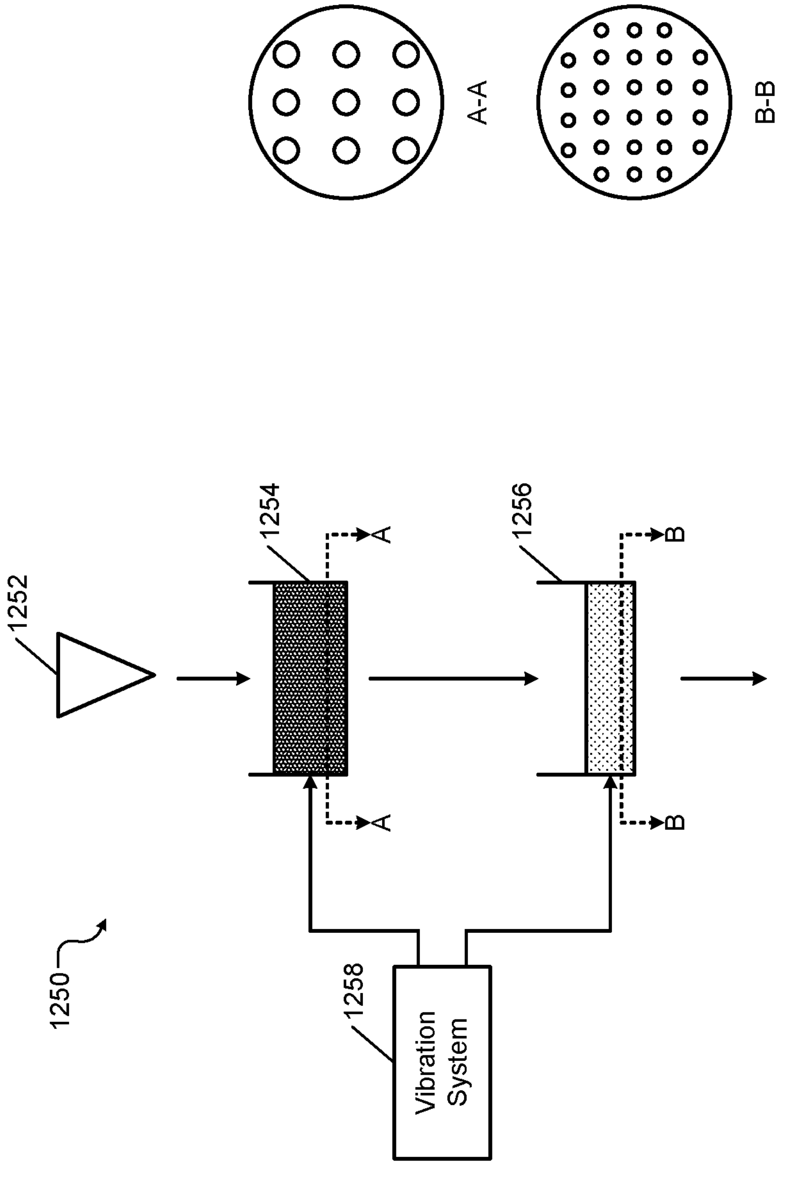


FIG. 10D

FIG. 10E

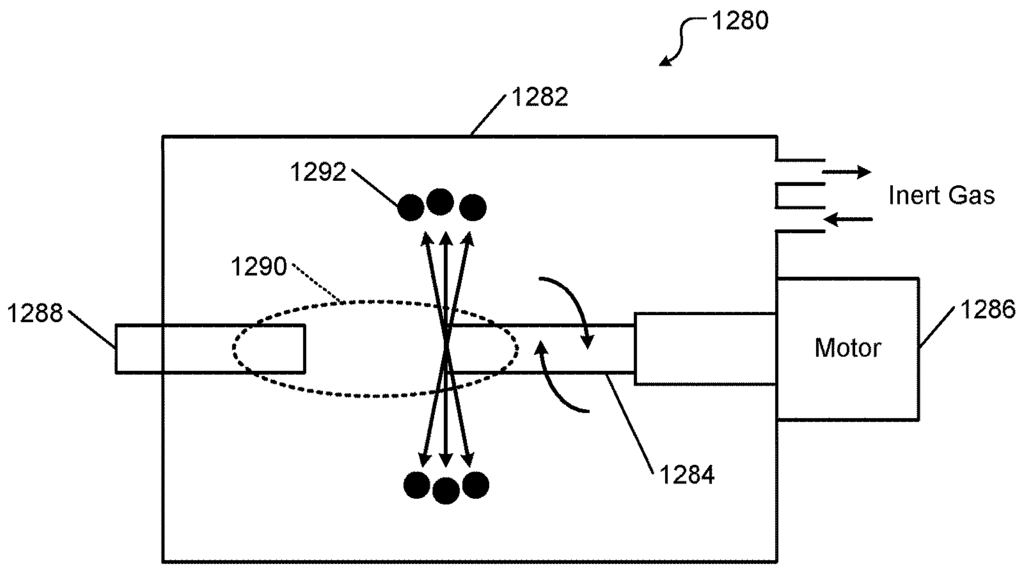
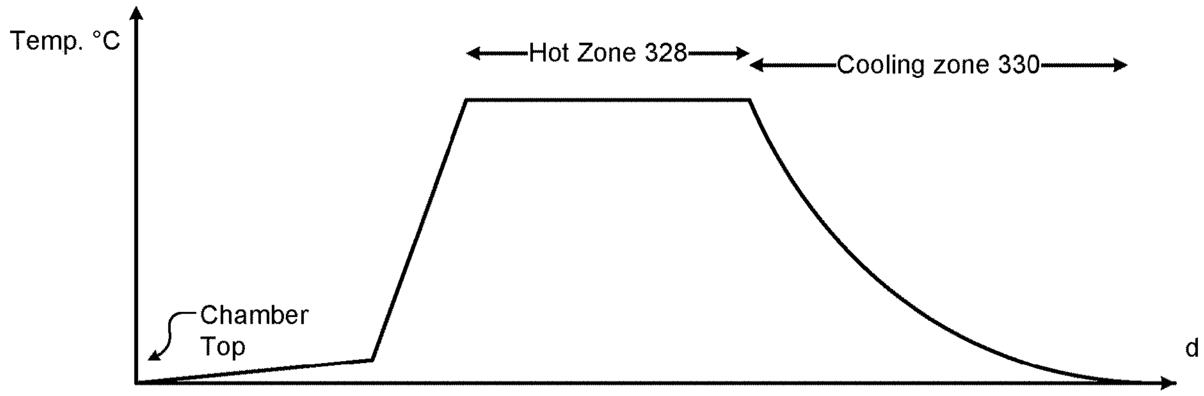


FIG. 10G



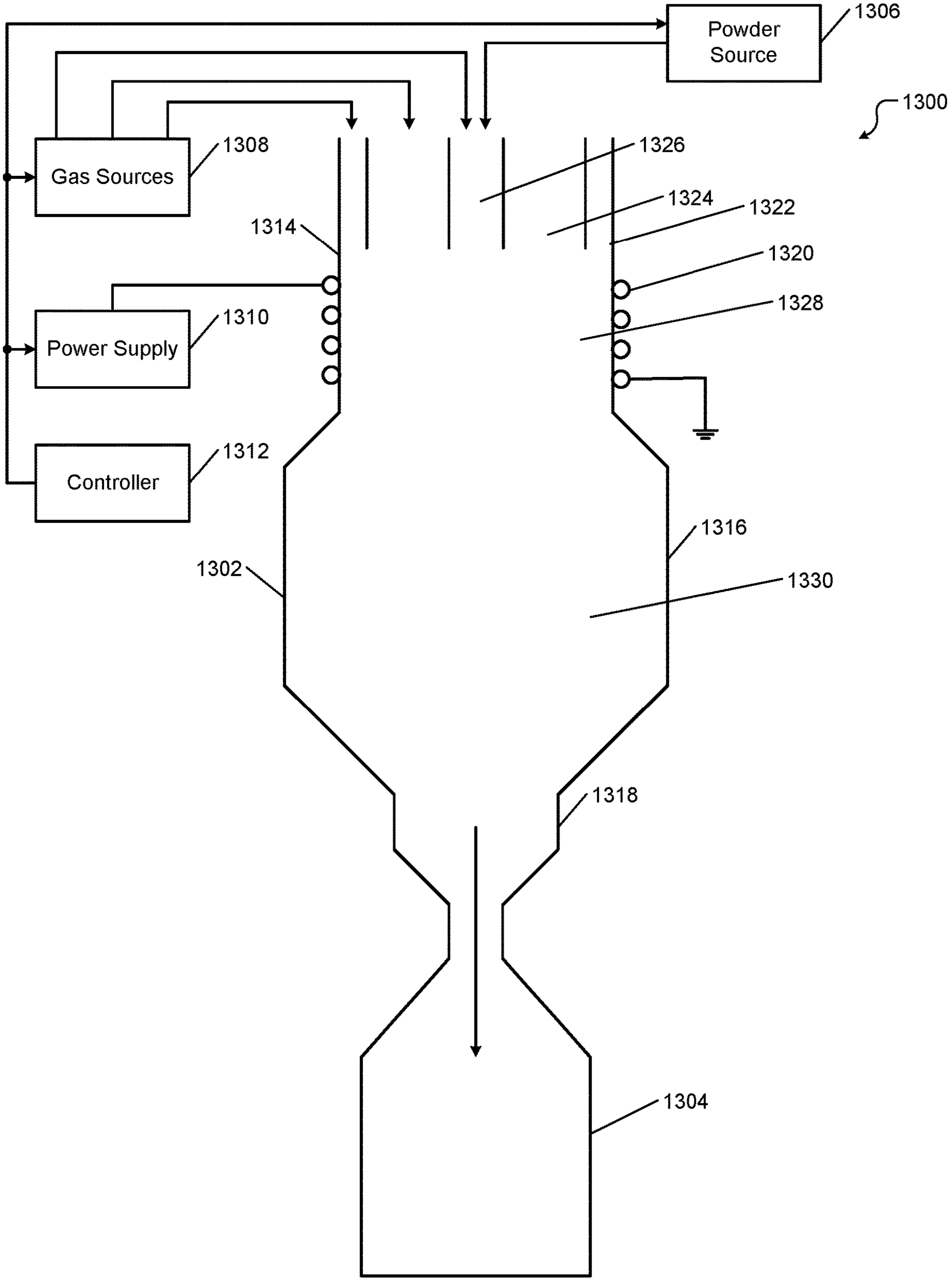

Powder Source
1306
1300
Gas Sources
1308
1326
1324
1322
1314
1320
Power Supply
1310
1328
Controller
1312
1316
1302
1330
1318
1304

FIG. 10F

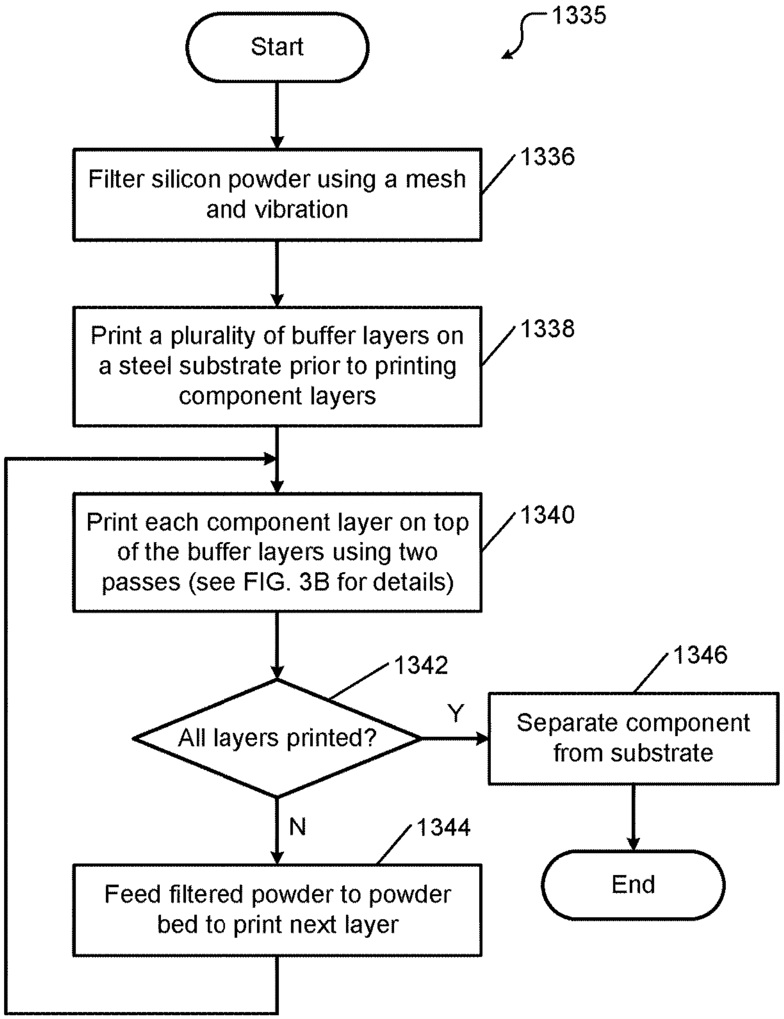


FIG. 11A

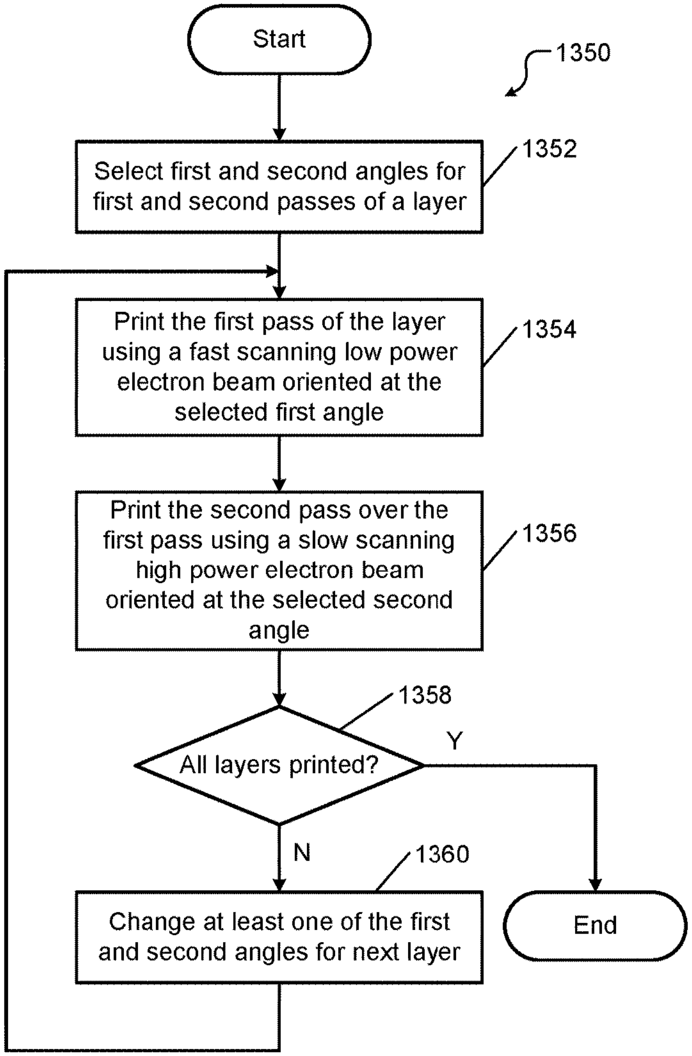


FIG. 11B

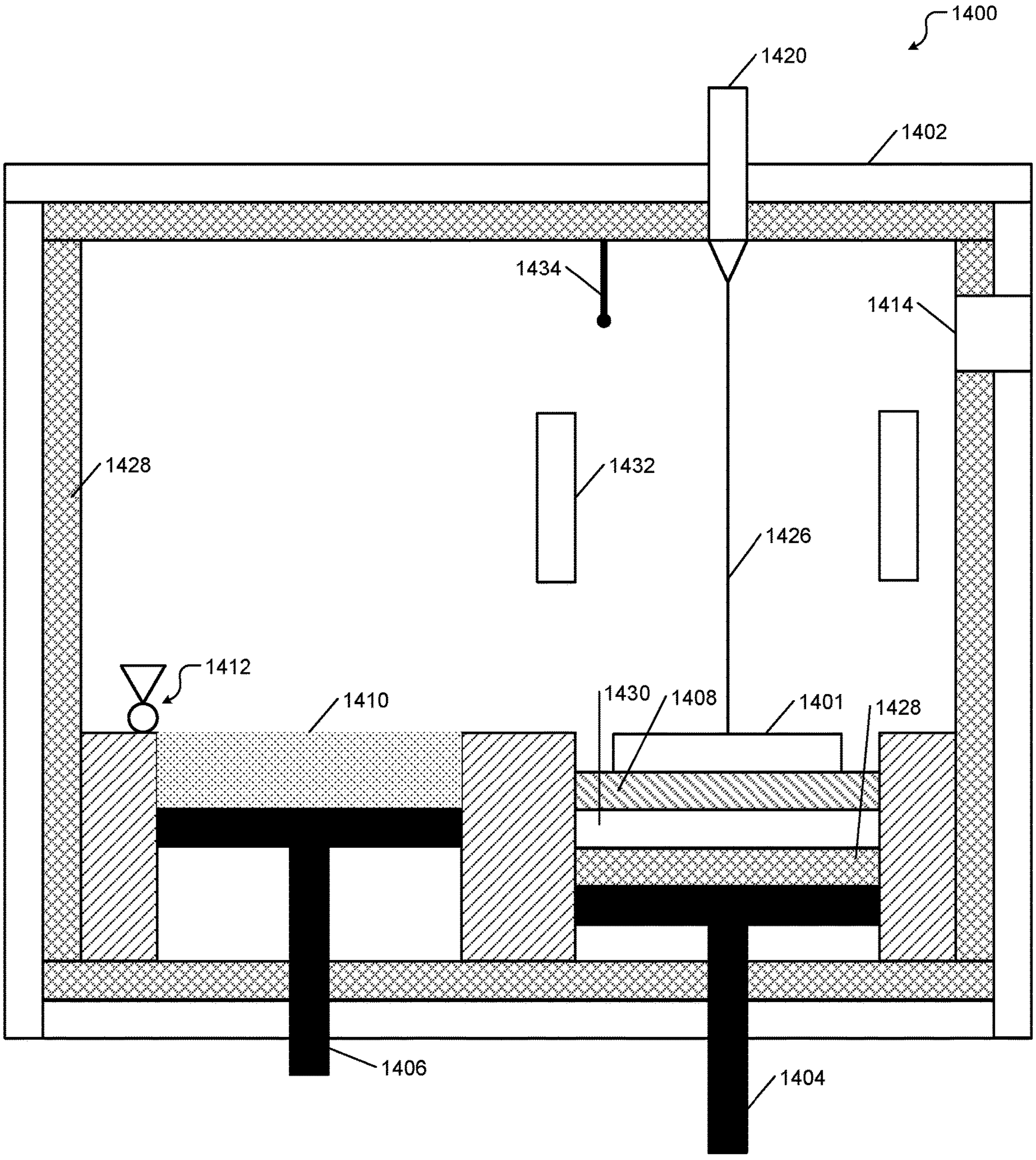

1400
1420
1402
1434
1414
1428
1432
1426
1412
1410
1430
1408
1401
1428
1406
1404

FIG. 12A

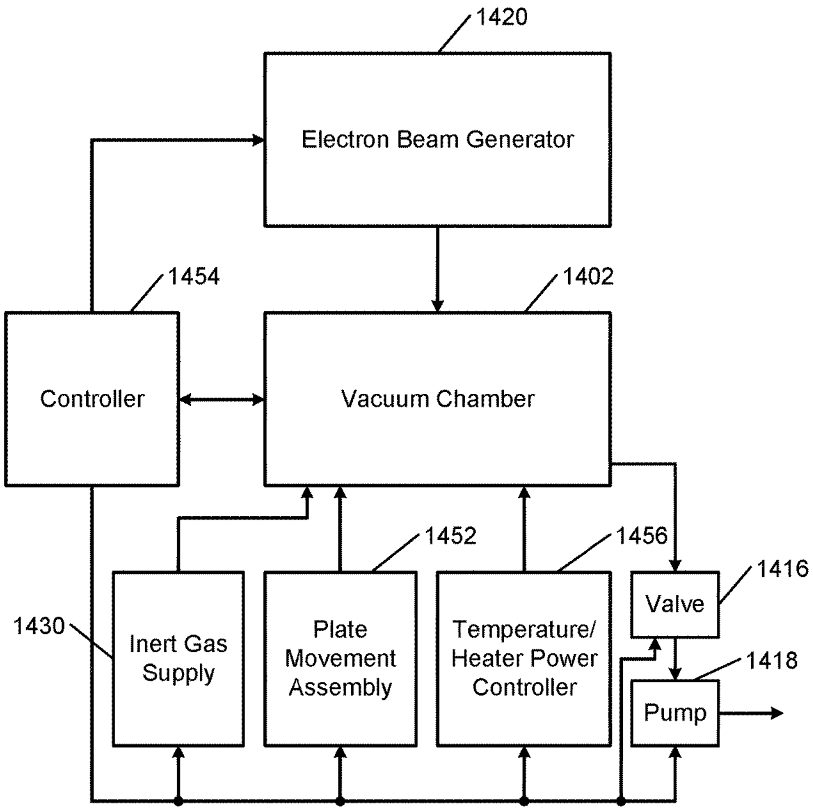


FIG. 12B

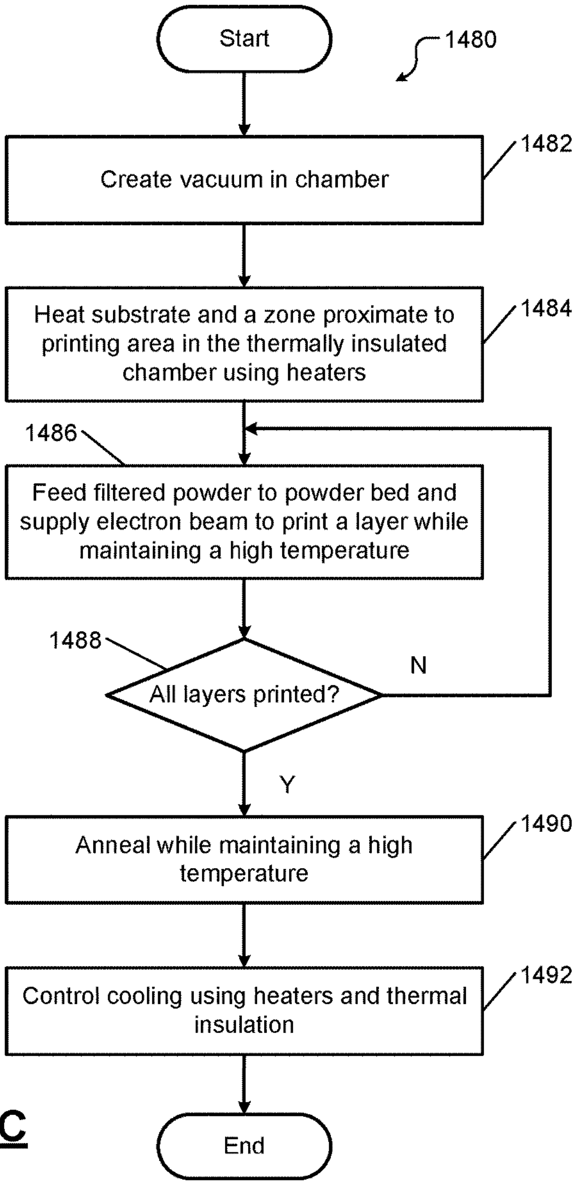


FIG. 12C

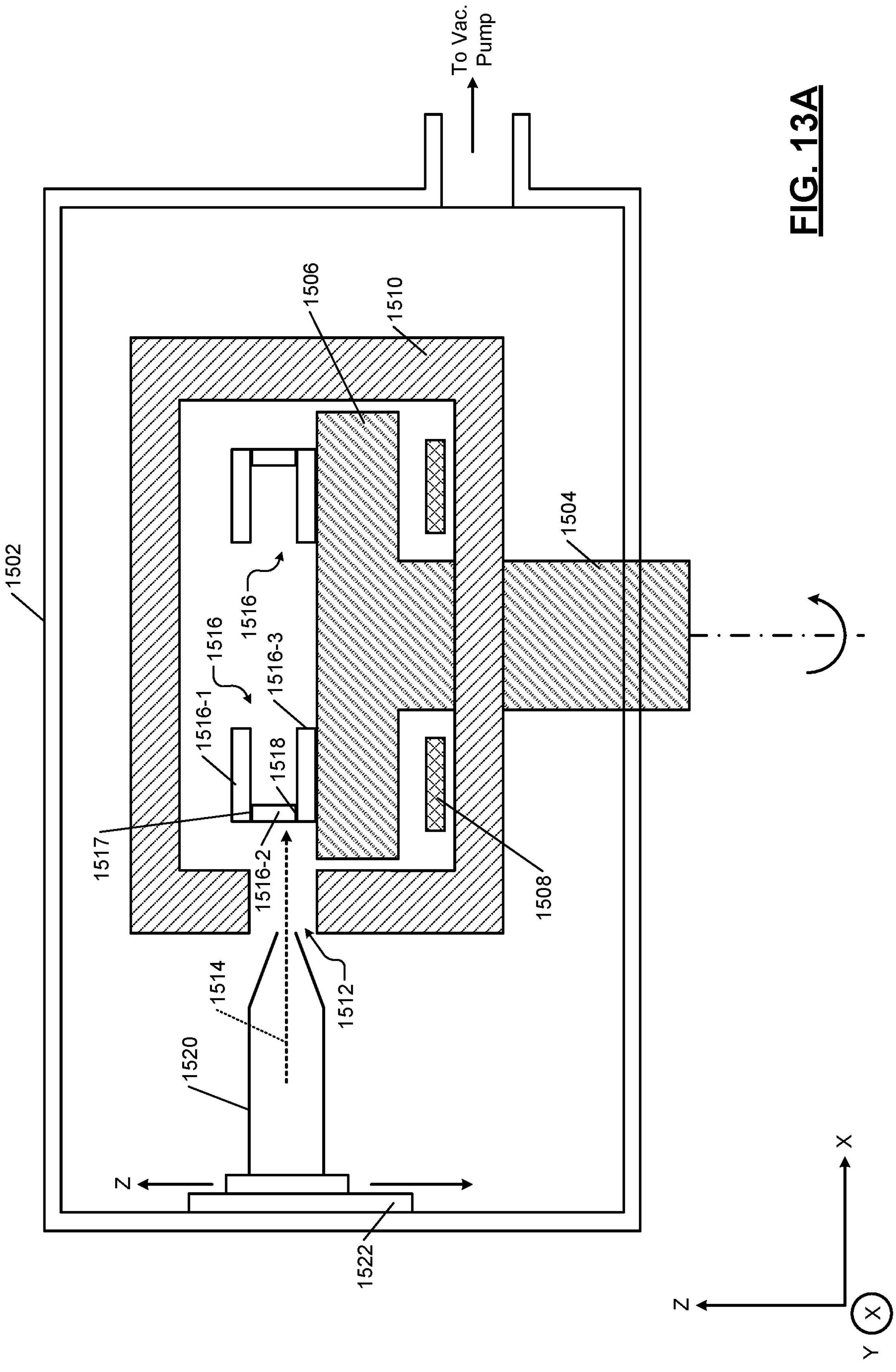

To Vac. Pump
1502
1506
1510
1504
1516
1516
1516-1
1516-3
1518
1517
1516-2
1508
1514
1520
1512
1522
Z
X
Z
Y

FIG. 13A

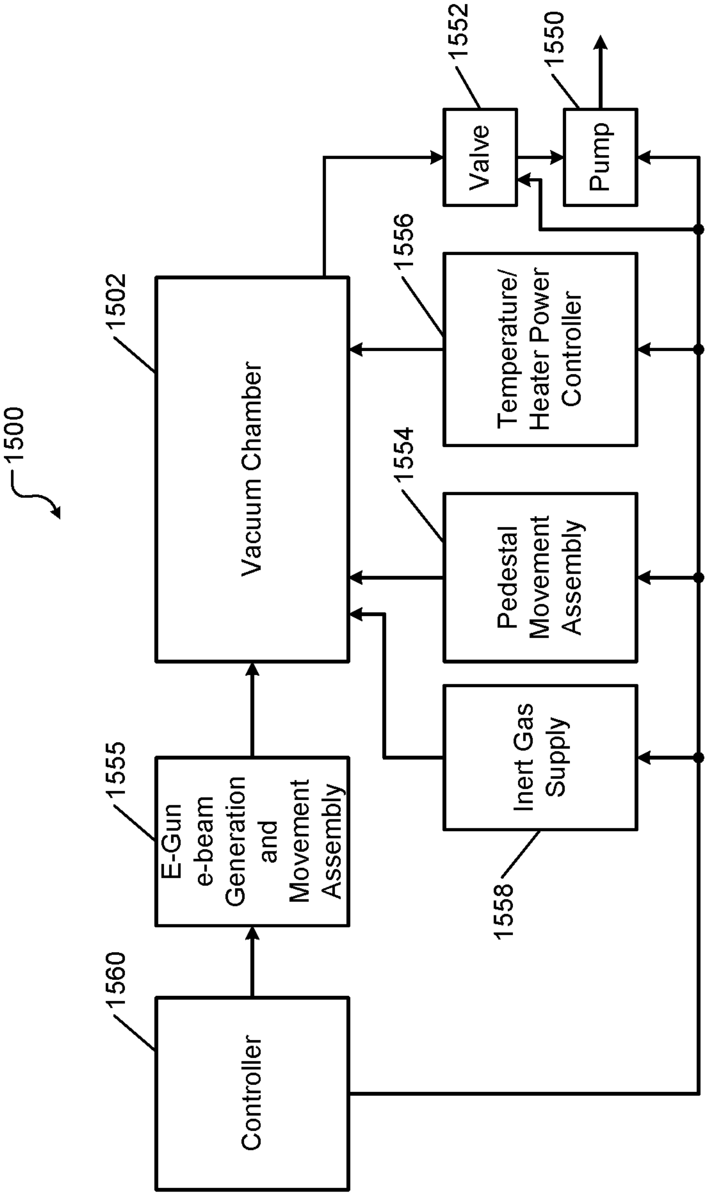

1500
1502
Vacuum Chamber
1552
Valve
1550
Pump
1556
Temperature/ Heater Power Controller
1554
Pedestal Movement Assembly
1558
Inert Gas Supply
1555
E-Gun e-beam Generation and Movement Assembly
1560
Controller

FIG. 13B

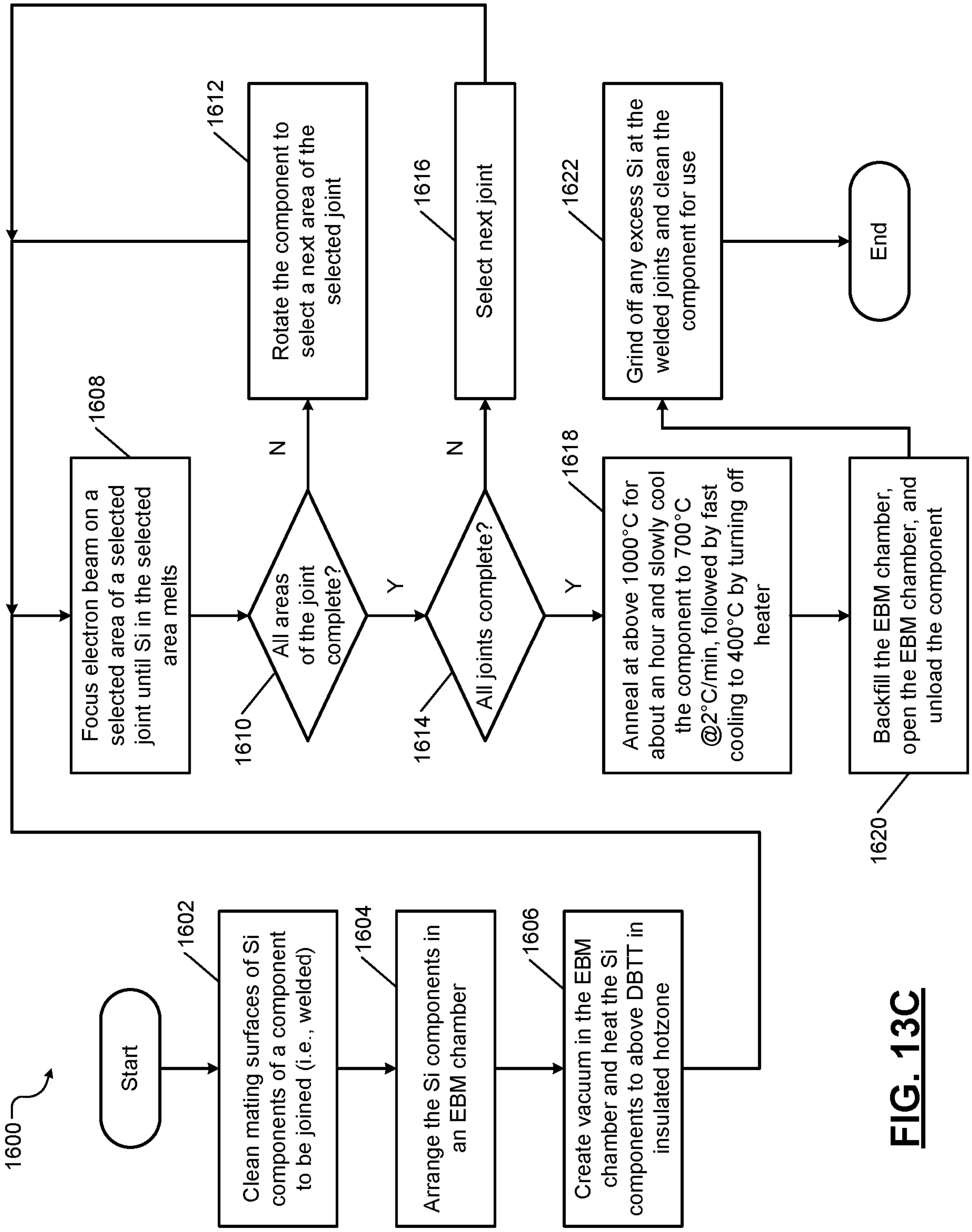

1600
Start
1602
Clean mating surfaces of Si components of a component to be joined (i.e., welded)
1604
Arrange the Si components in an EBM chamber
1606
Create vacuum in the EBM chamber and heat the Si components to above DBTT in insulated hotzone
1608
Focus electron beam on a selected area of a selected joint until Si in the selected area melts
1610
All areas of the joint complete?
N
1612
Rotate the component to select a next area of the selected joint
Y
1614
All joints complete?
N
1616
Select next joint
Y
1618
Anneal at above 1000°C for about an hour and slowly cool the component to 700°C @2°C/min, followed by fast cooling to 400°C by turning off heater
1620
Backfill the EBM chamber, open the EBM chamber, and unload the component
1622
Grind off any excess Si at the welded joints and clean the component for use
End

FIG. 13C

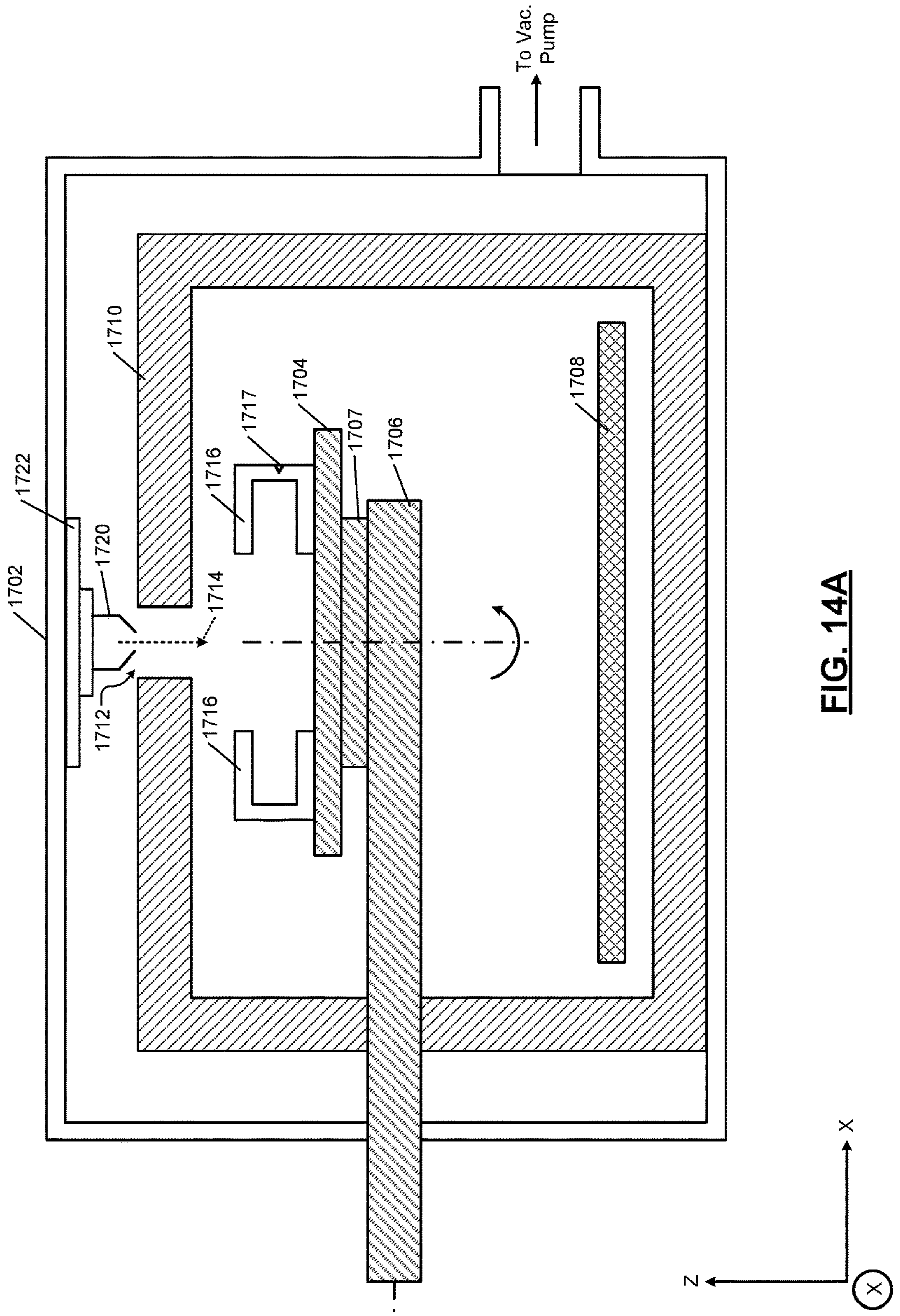

To Vac. Pump
1710
1722
1702
1720
1712
1714
1716
1716
1717
1704
1707
1706
1708
X
Z
Y

FIG. 14A

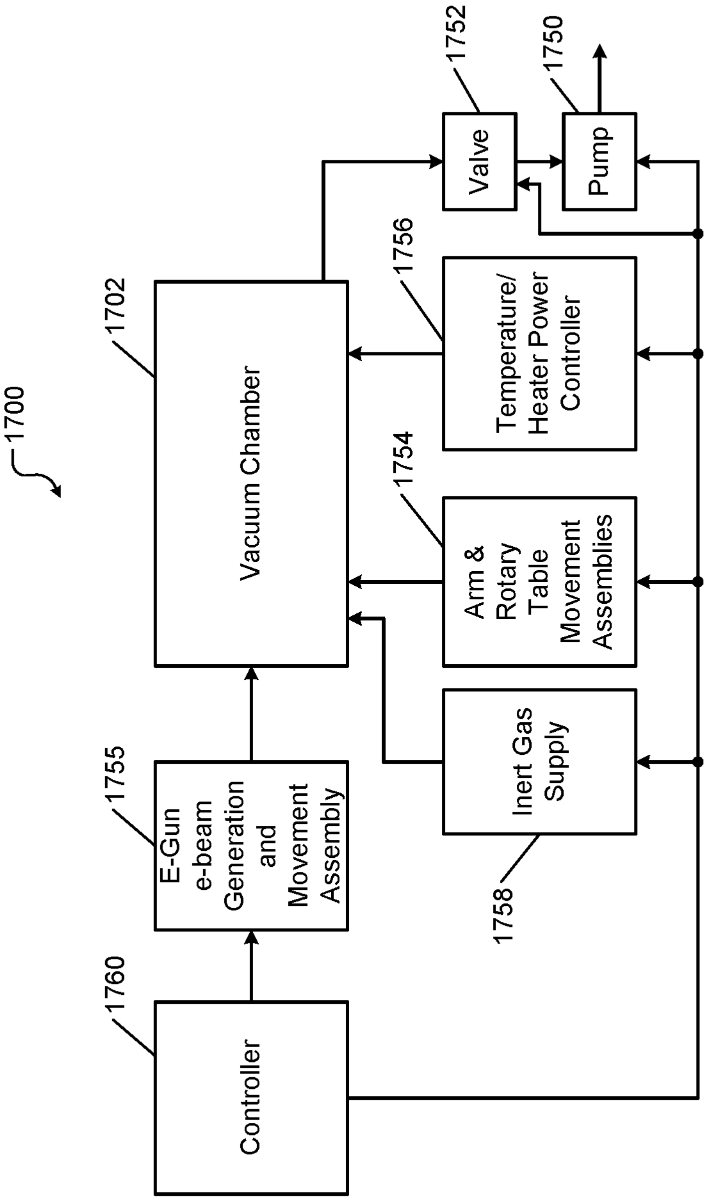

1700
1702
Vacuum Chamber
1752
Valve
1750
Pump
1756
Temperature/ Heater Power Controller
1754
Arm & Rotary Table Movement Assemblies
1755
E-Gun e-beam Generation and Movement Assembly
1758
Inert Gas Supply
1760
Controller

FIG. 14B

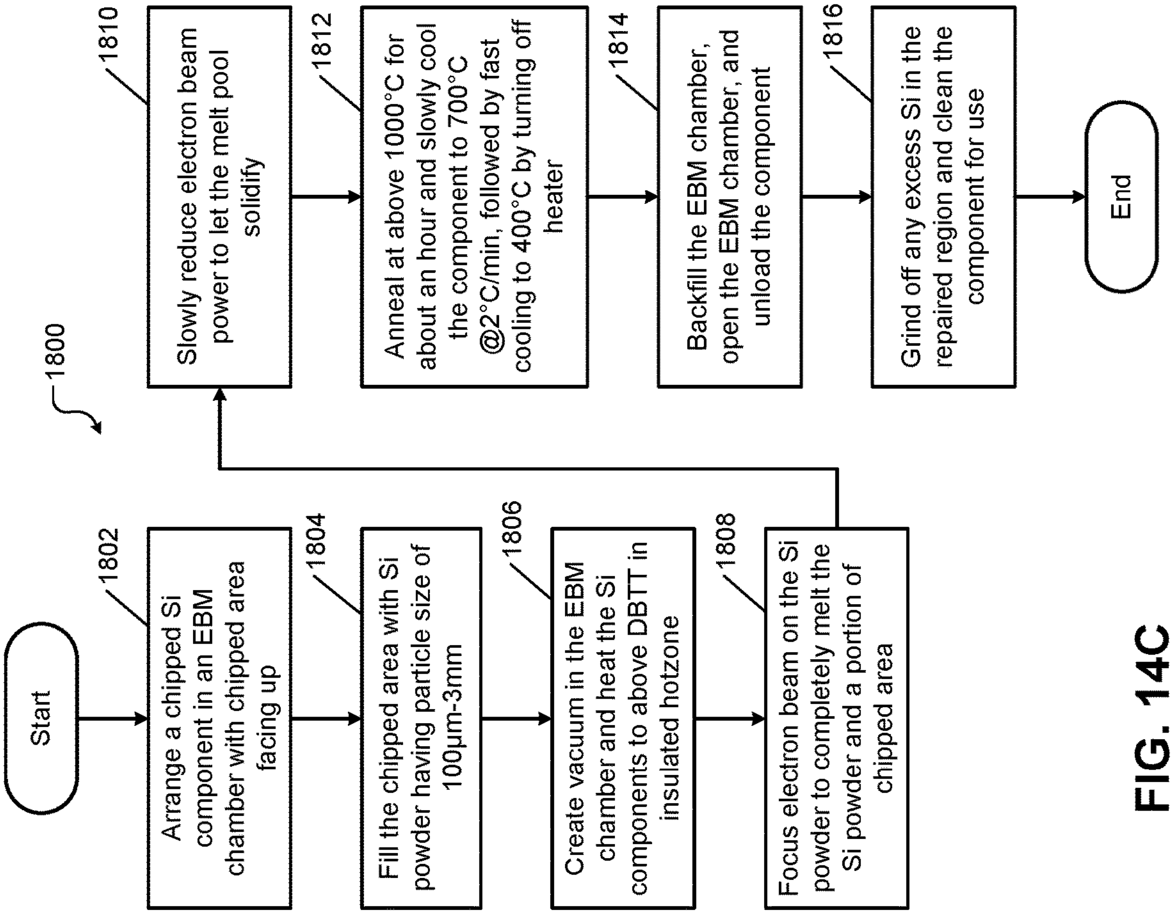

1800
Start
1802
Arrange a chipped Si component in an EBM chamber with chipped area facing up
1804
Fill the chipped area with Si powder having particle size of 100µm-3mm
1806
Create vacuum in the EBM chamber and heat the Si components to above DBTT in insulated hotzone
1808
Focus electron beam on the Si powder to completely melt the Si powder and a portion of chipped area
1810
Slowly reduce electron beam power to let the melt pool solidify
1812
Anneal at above 1000°C for about an hour and slowly cool the component to 700°C @2°C/min, followed by fast cooling to 400°C by turning off heater
1814
Backfill the EBM chamber, open the EBM chamber, and unload the component
1816
Grind off any excess Si in the repaired region and clean the component for use
End

FIG. 14C

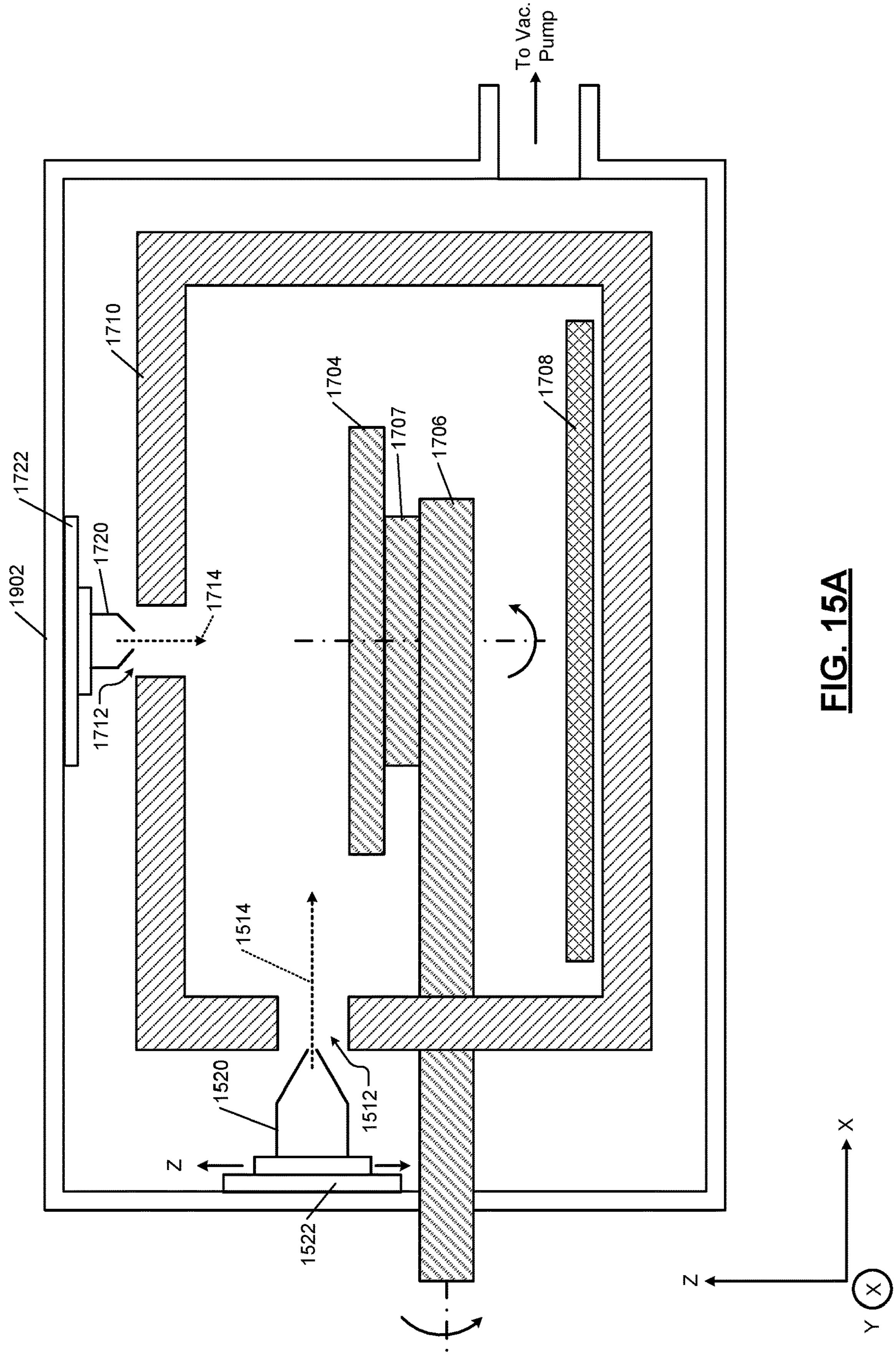

To Vac. Pump
1722
1720
1902
1714
1712
1710
1704
1707
1706
1708
1514
1520
1512
Z
1522
X
Z
Y

FIG. 15A

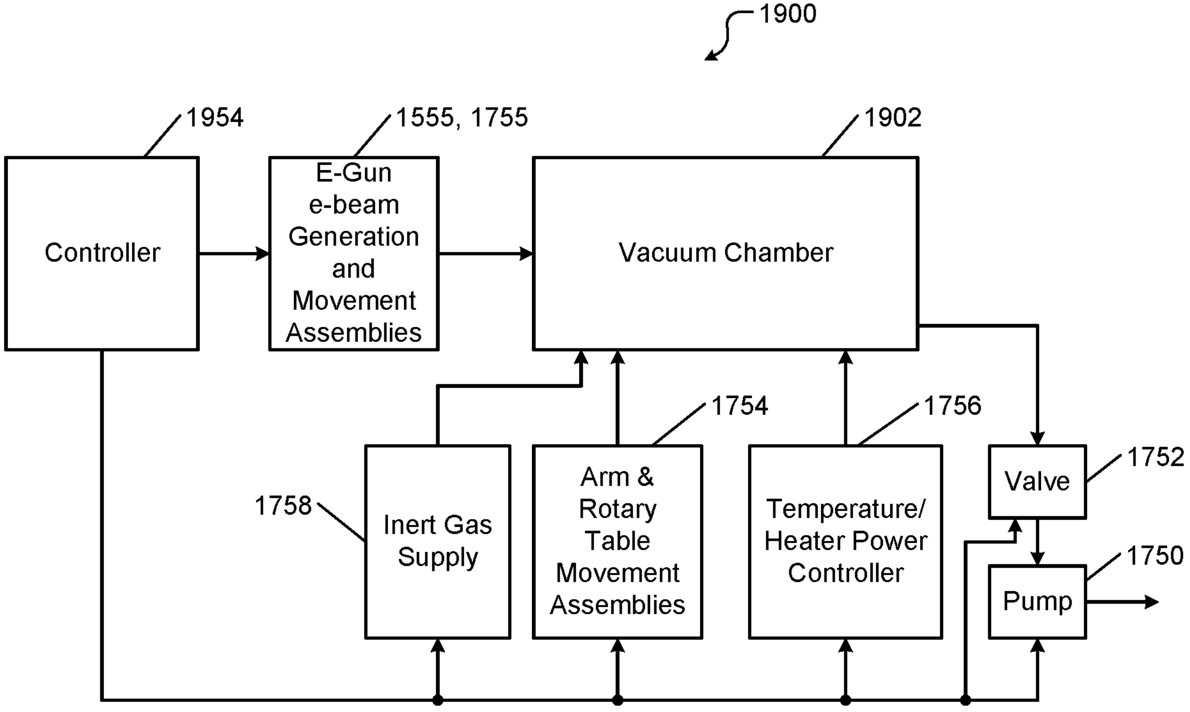

1900
1954
Controller
1555, 1755
E-Gun
e-beam
Generation
and
Movement
Assemblies
1902
Vacuum Chamber
1758
Inert Gas
Supply
1754
Arm &
Rotary
Table
Movement
Assemblies
1756
Temperature/
Heater Power
Controller
1752
Valve
1750
Pump

FIG. 15B

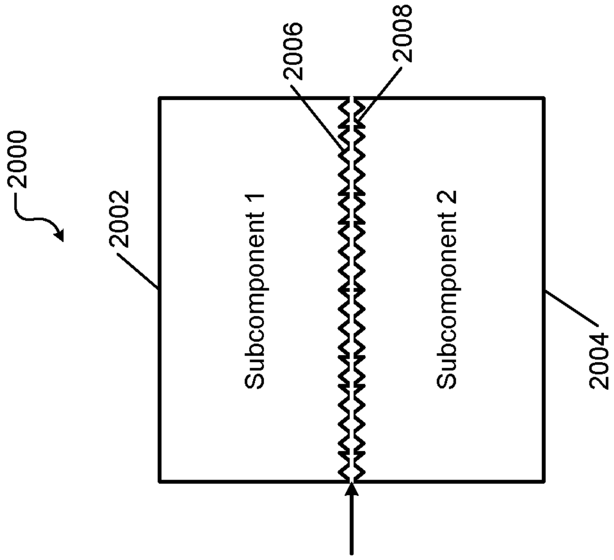


FIG. 16A

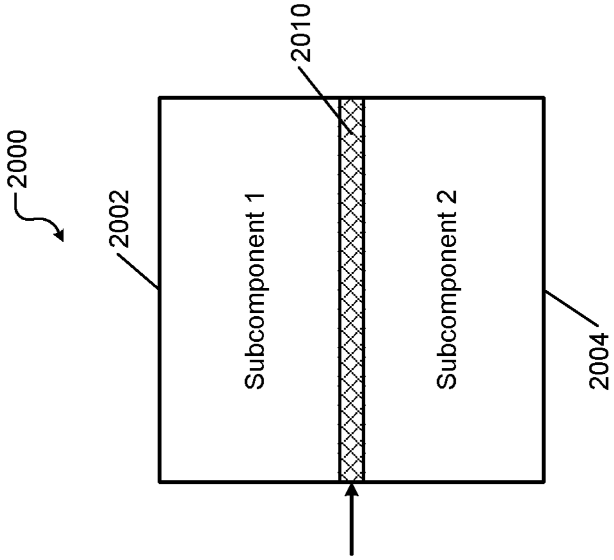


FIG. 16B

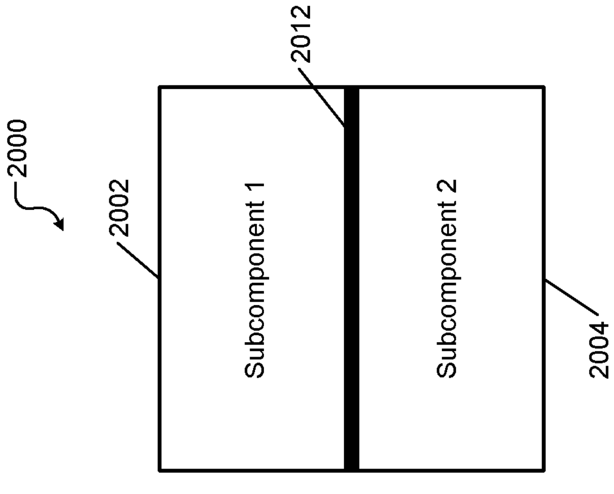


FIG. 16C

ADDITIVE MANUFACTURING OF SILICON COMPONENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/021,528, filed on May 7, 2020 and U.S. Provisional Application No. 63/128,925, filed on Dec. 22, 2020. The entire disclosures of the applications referenced above are incorporated herein by reference.

FIELD

[0002] The present disclosure relates generally to manufacturing silicon components and more particularly to 3D printing of fully dense and crack free silicon using electron beam melting.

BACKGROUND

[0003] The background description provided here is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

[0004] A substrate processing system typically includes a plurality of processing chambers (also called process modules) to perform deposition, etching, and other treatments of substrates such as semiconductor wafers. Examples of processes that may be performed on a substrate include, but are not limited to, a plasma enhanced chemical vapor deposition (PECVD) process, a chemically enhanced plasma vapor deposition (CEPVD) process, and a sputtering physical vapor deposition (PVD) process. Additional examples of processes that may be performed on a substrate include, but are not limited to, etching (e.g., chemical etching, plasma etching, reactive ion etching, etc.) and cleaning processes.

[0005] During processing, a substrate is arranged on a substrate support such as a pedestal, an electrostatic chuck (ESC), and so on in a processing chamber of the substrate processing system. During deposition, gas mixtures including one or more precursors are introduced into the processing chamber, and plasma is struck to activate chemical reactions. During etching, gas mixtures including etch gases are introduced into the processing chamber, and plasma is struck to activate chemical reactions. A computer-controlled robot typically transfers substrates from one processing chamber to another in a sequence in which the substrates are to be processed.

[0006] Various types of components, such as components for semiconductor processing chamber applications, currently use subtractive-machining methods to remove silicon from a larger block of silicon to make components. One problem encountered when using subtractive-machining methods however is that it is difficult or impossible to make parts with complex features, such as gas plenum, curved gas holes, or entire monolithic-silicon process chambers (such chambers are typically formed as three or more pieces and then later assembled into a whole chamber). Another problem of the subtractive-machining methods used currently is that materials utilization is poor since frequently extremely large portions of the larger block of silicon to make components must be removed, and frequently wasted, to make the machined components.

[0007] Other technologies recently attempted have focused on additive-manufacturing techniques using silicon. However, these attempts have produced silicon components with residual stress and induced cracks. The cracks in the silicon weaken the structure of the manufactured components.

[0008] The information described in this section is provided to offer the skilled artisan a context for the following disclosed subject matter and should not be considered as admitted prior art.

SUMMARY

[0009] In one exemplary embodiment, the disclosed subject matter describes a method of performing three-dimensional (3D) printing of a silicon component, the method including adding powdered silicon to a 3D printing tool. For each layer of the 3D printing in a layer-by-layer process: forming a powder bed of the powdered silicon in the 3D printing tool, baking the powdered silicon in a temperature range of 650° C. to 750° C. under a high-vacuum condition in a range of 10^{-5} Torr to 10^{-7} Torr to decompose and remove surface oxides from the powdered silicon, forming a layer of the powder bed to a pre-determined thickness, directing a high-powered beam under the high-vacuum condition in a pre-determined pattern into the formed powder-bed, the high-powered beam having sufficient energy to melt the powdered silicon, and making a determination as to whether additional layers in the 3D printing are needed. Based on a determination that no additional layers are needed, cooling the silicon component at a pre-determined temperature ramp-down rate to about ambient temperature of an environment in which the 3D printing tool is located.

[0010] In another exemplary embodiment, the disclosed subject matter describes a method of performing three-dimensional (3D) printing of a silicon component, the method including loading a design file into a 3D printing tool where the design file containing geometries of the silicon component including coordinates for each of multiple layers to print the silicon component. For each layer of the 3D printing of the silicon component: forming a powder bed of powdered silicon in the 3D printing tool, baking the powdered silicon in a temperature range of 650° C. to 750° C. under a high-vacuum condition in a range of 10^{-5} Torr to 10^{-7} Torr to decompose and remove surface oxides from the powdered silicon, raking a layer of the powder bed to a pre-determined thickness, directing an electron beam under the high-vacuum condition in a pre-determined pattern into the raked powdered-bed, the pre-determined pattern being based on the design file, the electron beam having sufficient energy to melt the powdered silicon, and making a determination as to whether additional layers in the 3D printing are needed. Based on a determination that no additional layers are needed, cooling the silicon component at a pre-determined temperature to about ambient temperature in which the 3D printing tool is located.

[0011] Various systems and apparatuses for performing the exemplary methods, as well as other methods, are described in detail herein.

[0012] A system for printing a fully dense component of a nonmetallic material, the system comprises a chamber under vacuum. A first vertically movable plate is arranged in the chamber to support a substrate. A second vertically movable plate is arranged adjacent to the first vertically movable plate. The second vertically movable plate is configured to store a powder of the nonmetallic material and to dose the substrate with the powder prior to printing each layer of the nonmetallic material. An electron beam generator is configured to supply an electron beam. A controller is configured to print a plurality of layers of the nonmetallic material on the substrate using the electron beam and to print a layer of the nonmetallic material on the plurality of layers to build the component on the plurality of layers by: printing a first sublayer of the layer of the nonmetallic material using the electron beam having a first power and a first speed and by printing a second sublayer of the layer of the nonmetallic material on the first sublayer using the electron beam having a second power and a second speed. The first speed is greater than the second speed. The first power is less than the second power.

[0013] In another feature, the nonmetallic material comprises particles having a diameter within a range of 40-100 μm.

[0014] In other features, the controller is further configured to print the first sublayer using the electron beam having a first orientation and to print the second sublayer using the electron beam having a second orientation that is different than the first orientation.

[0015] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0016] In other features, the system further comprises one or more meshes having holes of different diameters and a vibrating system configured to vibrate the one or more meshes. The powder is selected from a stock by passing the stock through the one or more meshes. The selected powder comprises particles having a diameter within a range of 40-100 μm.

[0017] In another feature, the system further comprises a plate movement assembly configured to move the first vertically movable plate in a downward direction after printing each layer and to move the second vertically movable plate in an upward direction after printing each layer.

[0018] In still other features, a method of printing a fully dense component of a nonmetallic material on a substrate comprises printing a plurality of layers of the nonmetallic material on the substrate using an electron beam. The method further comprises printing a layer of the nonmetallic material on the plurality of layers to build the component on the plurality of layers by: printing a first sublayer of the layer of the nonmetallic material using the electron beam having a first power and a first speed and by printing a second sublayer of the layer of the nonmetallic material on the first sublayer using the electron beam having a second power and a second speed. The first speed is greater than the second speed. The first power is less than the second power.

[0019] In another feature, the nonmetallic material comprises particles having a diameter within a range of 40-100 μm.

[0020] In other features, the method further comprises printing the first sublayer using the electron beam having a first orientation and printing the second sublayer using the electron beam having a second orientation that is different than the first orientation.

[0021] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0022] In another feature, the method further comprises supplying a dose of a powder of the nonmetallic material before printing each layer. The powder comprises particles having a diameter within a range of 40-100 μm.

[0023] In another feature, the method further comprises selecting the powder from a stock by passing the stock through one or more meshes having holes of different diameters and by vibrating the one or more meshes.

[0024] In another feature, the method further comprises printing the component in a chamber under vacuum.

[0025] In still other features, a method of printing a component of a nonmetallic material on a substrate comprises printing a plurality of layers of the nonmetallic material on the substrate using an electron beam. The plurality of layers form a base on which to build the component. The method further comprises building the component on the plurality of layers by printing one or more layers of the nonmetallic material on the plurality of layers using the electron beam.

[0026] In another feature, the nonmetallic material comprises particles having a diameter within a range of 40-100 μm.

[0027] In other features, printing each layer of the one or more layers comprises printing a first sublayer of the nonmetallic material using the electron beam having a first power and a first speed and printing a second sublayer of the nonmetallic material on the first sublayer using the electron beam having a second power and a second speed. The first speed is greater than the second speed. The first power is less than the second power.

[0028] In other features, the method further comprises printing the first sublayer using the electron beam having a first orientation and printing the second sublayer using the electron beam having a second orientation that is different than the first orientation.

[0029] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0030] In other features, the method further comprises supplying a dose of a powder of the nonmetallic material before printing each layer. The powder comprises particles having a diameter within a range of 40-100 μm.

[0031] In another feature, the method further comprises selecting the powder from a stock by passing the stock through one or more meshes having holes of different diameters and by vibrating the one or more meshes.

[0032] In still other features, a method of printing a fully dense component of a nonmetallic material on a substrate comprises printing a first sublayer of a layer of the nonmetallic material on the substrate using an electron beam having a first power and a first speed. The method further comprises printing a second sublayer of the layer of the nonmetallic material on the first sublayer using the electron beam having a second power and a second speed. The first speed is greater than the second speed. The first power is less than the second power.

[0033] In another feature, the nonmetallic material comprises particles having a diameter within a range of 40-100 μm.

[0034] In other features, the method further comprises printing the first sublayer using the electron beam having a first orientation and printing the second sublayer using the electron beam having a second orientation that is different than the first orientation.

[0035] In another feature, the method further comprises printing a plurality of layers of the nonmetallic material on the substrate using the electron beam prior to printing the layer.

[0036] In another feature, the plurality of layers form a base on which the component is built by printing the layer.

[0037] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0038] In another feature, the method further comprises supplying a dose of a powder of the nonmetallic material before printing each layer. The powder comprises particles having a diameter within a range of 40-100 μm.

[0039] In another feature, the method further comprises selecting the powder from a stock by passing the stock through one or more meshes having holes of different diameters and by vibrating the one or more meshes.

[0040] In still other features, a system for printing a fully dense and crack free component of a nonmetallic material on a substrate made of the nonmetallic material comprises a chamber for printing the fully dense and crack free component, the chamber being thermally insulated. The system further comprises a first vertically movable plate arranged in the chamber to support the substrate and a thermally insulating material arranged on a top surface of the first vertically movable plate and under the substrate. The system further comprises a heater configured to heat the substrate and a region of the chamber surrounding the substrate prior to printing the component on the substrate. The system further comprises a powder feeder configured to supply a powder of the nonmetallic material and an electron generator configured to supply an electron beam to print a layer of the nonmetallic material on the substrate while the heater continues to heat the substrate and the region of the chamber surrounding the substrate during the printing.

[0041] In another feature, the powder comprises particles having a diameter within a range of 40-100 μm.

[0042] In another feature, the heater is configured to heat the substrate and the region of the chamber surrounding the substrate to a temperature greater than a ductile to brittle transition temperature of the nonmetallic material during the printing of the component.

[0043] In another feature, after the printing, the heater is configured to continue heating the substrate and the region of the chamber surrounding the substrate while annealing the component in the chamber.

[0044] In another feature, after the printing, the component remains surrounded by the powder while the component slowly cools at a controlled rate.

[0045] In another feature, the chamber is thermally insulated with one or more of layers of one or more insulating materials.

[0046] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0047] In another feature, the heater is arranged under the substrate or surrounding the substrate and the region of the chamber above the substrate.

[0048] In other features, the powder feeder comprises a second vertically movable plate arranged adjacent to the first vertically movable plate, and the second vertically movable plate is configured to store the powder and to dose the substrate with the powder prior to printing each layer of the nonmetallic material.

[0049] In another feature, the system further comprises a plate movement assembly configured to move the first vertically movable plate in a downward direction after printing each layer and to move the second vertically movable plate in an upward direction after printing each layer.

[0050] In another feature, the system further comprises one or more additional heaters configured to heat a region of the chamber above the substrate during the printing of the component.

[0051] In another feature, the chamber is under vacuum.

[0052] In other features, the system further comprises one or more meshes having holes of different diameters and a vibrating system configured to vibrate the one or more meshes. The powder is selected from a stock by passing the stock through the one or more meshes. The selected powder comprises particles having a diameter within a range of 40-100 μm.

[0053] In still other features, a method of printing a fully dense and crack free component of a nonmetallic material on a substrate made of the nonmetallic material in a chamber comprises heating the substrate and a region of the chamber surrounding the substrate prior to printing a layer of the nonmetallic material on the substrate. The method further comprises printing the layer of the nonmetallic material on the substrate using an electron beam while continuing to heat the substrate and the region of the chamber surrounding the substrate during the printing.

[0054] In another feature, the nonmetallic material comprises particles having a diameter within a range of 40-100 μm.

[0055] In another feature, the method further comprises heating the substrate and the region of the chamber surrounding the substrate to a temperature greater than a ductile to brittle transition temperature of the nonmetallic material during the printing of the component.

[0056] In another feature, the method further comprises after the printing, annealing and slow cooling the component in the chamber while continuing to heat the substrate and the region of the chamber surrounding the substrate.

[0057] In another feature, the method further comprises after the printing, cooling the component by surrounding the component with a powder of the nonmetallic material.

[0058] In another feature, the method further comprises thermally insulating the chamber using one or more of layers of one or more insulating materials.

[0059] In another feature, the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0060] In other features, the method further comprises dosing the substrate with the nonmetallic material prior to printing each layer of the layer of the nonmetallic material, and supplying the electron beam subsequent to the dosing to print each layer of the nonmetallic material.

[0061] In another feature, the method further comprises heating a region of the chamber above the substrate during the printing of the component.

[0062] In another feature, the method further comprises maintaining vacuum in the chamber.

[0063] In another feature, the method further comprises maintaining a vacuum in the chamber.

[0064] In other features, the method further comprises selecting a powder of the nonmetallic material from a stock by passing the stock through one or more meshes having holes of different diameters and by vibrating the one or more meshes. The selected powder comprises particles having a diameter within a range of 40-100 μm.

[0065] In still other features, a system comprises a chamber including an upper portion having an inlet to receive silicon powder, a carrier gas, and a dopant; a middle portion connected to the upper portion; and a third portion connected to the middle portion and having an outlet. The system comprises a coil arranged around the upper portion and a power supply configured to supply power to the coil. The system comprises a controller configured to control supply of the silicon powder, the carrier gas, and the dopant to the inlet and to control the power supplied to the coil to generate plasma. The outlet outputs a spherical shaped, dense, and doped silicon powder.

[0066] In other features, the middle portion has a greater cross-sectional area than the upper portion. The third portion has a smaller cross-sectional area than the upper portion.

[0067] In other features, the upper portion includes an inner tube, a middle tube coaxially surrounding the inner tube, and an outer tube defined by an outer wall of the middle tube and an inner wall of the upper portion. The inner, middle, and the outer tubes extend vertically downwards from a top end of the upper portion to a midpoint of the upper portion. The coil is arranged around the upper portion between the midpoint of the upper portion and a bottom end of the upper portion.

[0068] In other features, the silicon powder is supplied to the inner tube, and the system further comprises a first gas source to supply the carrier gas to mix with the silicon powder, a second gas source to supply the dopant to the middle tube, and a third gas source to supply a sheath gas to the outer tube.

[0069] In still other features, a method of building a component for a substrate processing system comprises arranging first and second subcomponents of the component in a thermally insulated zone in a chamber under vacuum and heating the first and second subcomponents in the thermally insulated zone to a predetermined temperature. The method comprises bonding a first end of the first subcomponent to a second end of the second subcomponent by partially melting material at the first and second ends using an electron beam followed by solidifying the melted material. The method comprises annealing the bonded first and second subcomponents to form the component, cooling the formed component to a first temperature at a first rate, and cooling the formed component to a second temperature at a second rate. The second temperature is less than the first temperature. The first rate is slower than the second rate.

[0070] In another feature, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0071] In another feature, the method further comprises bonding the first and second subcomponents without using any additional material.

[0072] In another feature, the method further comprises cleaning mating surfaces of the first and second ends before the melting.

[0073] In another feature, the method further comprises grinding excess material from the component and cleaning the component.

[0074] In still other features, a method of repairing a component used in a substrate processing system comprises arranging the component in a thermally insulated zone in a chamber under vacuum, adding a powdered material to a defective region of the component, heating the component in the thermally insulated zone to a predetermined temperature, and melting the powdered material and a portion of the defective region of the component using an electron beam to form a melt pool. The method comprises reducing a power of the electron beam to let the melted pool to solidify, annealing the component, cooling the component to a first temperature at a first rate, and cooling the component to a second temperature at a second rate. The second temperature is less than the first temperature. The first rate is slower than the second rate.

[0075] In other features, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics. The powdered material is the same nonmetallic material of which the component is made of.

[0076] In another feature, the method further comprises grinding excess material around the defective region of the component and cleaning the component.

[0077] In still other features, a system for building a component of a substrate processing system comprises a chamber under vacuum and a pedestal arranged in the chamber to support first and second subcomponents of the component thereon. The system comprises a heater arranged in the chamber proximate to the pedestal, and a thermal insulator arranged in the chamber forming a thermally insulated zone around the pedestal and the heater. The system comprises an electron beam generator arranged in the chamber to direct an electron beam onto ends of the first and second subcomponents through an opening in the thermally insulated zone to bond the ends together to form the component.

[0078] In other features, the system further comprises a first actuator configured to rotate the pedestal around a first axis, and a second actuator configured to move the electron beam generator along a second axis that is perpendicular to the first axis.

[0079] In another feature, the system further comprises a controller configured to control the heater to heat the first and second subcomponents to a predetermined temperature, and to control the electron beam generator to direct the electron beam onto the ends of the heated first and second subcomponents.

[0080] In another feature, the system further comprises a controller configured to control the heater to anneal the bonded first and second subcomponents to form an annealed component.

[0081] In another feature, the controller is configured to control the heater to cool the annealed component to a first temperature at a first rate, and to cool the annealed component to a second temperature at a second rate. The second temperature is less than the first temperature. The first rate is slower than the second rate.

[0082] In another feature, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0083] In still other features, a system for repairing a component of a substrate processing system comprises a chamber under vacuum, and a rotary table arranged in the chamber to support the component thereon. The component has a defective portion in which a powdered material is disposed. The system comprises an arm arranged in the chamber parallel to the rotary table. The arm has a first end coupled to the rotary table and a second end extending out of the chamber. The system comprises a heater arranged in the chamber proximate to rotary table and the arm, and a thermal insulator arranged in the chamber forming a thermally insulated zone around the heater, the rotary table, and the arm. The system comprises an electron beam generator arranged in the chamber to direct an electron beam onto the powdered material through an opening in the thermally insulated zone to melt the powdered material and to repair the defective portion of the component.

[0084] In other features, the system further comprises a first actuator configured to rotate the rotary table around a first axis, a second actuator configured to rotate the arm and the rotary table around a second axis that is perpendicular to the first axis, and a third actuator configured to move the electron beam generator parallel to the rotary table along third and fourth axes that are perpendicular to each other.

[0085] In another feature, the system further comprises a controller configured to control the heater to heat the component to a predetermined temperature, and to control the electron beam generator to direct the electron beam onto the powdered material in the defective portion of the heated component.

[0086] In another feature, the system further comprises a controller configured to control the heater to anneal the repaired component.

[0087] In another feature, the controller is configured to control the heater to cool the annealed component to a first temperature at a first rate, and to cool the annealed component to a second temperature at a second rate. The second temperature is less than the first temperature. The first rate is slower than the second rate.

[0088] In other features, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics. The powdered material is the same nonmetallic material of which the component is made of.

[0089] In still other features, a system for building and repairing components of a substrate processing system comprises a chamber under vacuum, and a rotary table arranged in the chamber. The system comprises an arm arranged in the chamber parallel to the rotary table. The arm has a first end coupled to the rotary table and a second end extending out of the chamber. The system comprises a heater arranged in the chamber proximate to rotary table and the arm, and a thermal insulator arranged in the chamber forming a thermally insulated zone around the heater, the rotary table, and the arm. The system comprises a first electron beam generator arranged in the chamber to direct a first electron beam towards the rotary table through a first opening in the thermally insulated zone. The system comprises a second electron beam generator arranged in the chamber to direct a second electron beam towards the rotary table through a second opening in the thermally insulated zone.

[0090] In another feature, the first and second electron beams are perpendicular to each other.

[0091] In other features, the system further comprises a first actuator configured to rotate the rotary table around a first axis, a second actuator configured to rotate the arm and the rotary table around a second axis that is perpendicular to the first axis, a third actuator configured to move the first electron beam generator parallel to the rotary table along third and fourth axes that are perpendicular to each other, and a fourth actuator configured to move the second electron beam generator along the first axis.

[0092] In another feature, the system further comprises a controller configured to control the heater to heat a component arranged on the rotary table to a predetermined temperature, and to control at least one of the first and second electron beam generator to direct at least one of the first and second electron beams onto the heated component.

[0093] In other features, the component includes two pieces. The at least one of the first and second electron beams melts ends of the two pieces and bonds the two pieces together.

[0094] In other features, the component includes a defective portion in which a powdered material is disposed. The at least one of the first and second electron beams melts the powdered material to repair the defective portion of the component.

[0095] In another feature, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0096] In other features, the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics. The powdered material is the same nonmetallic material of which the component is made of.

[0097] In another feature, the controller is configured to control the heater to anneal the heated component to form an annealed component.

[0098] In another feature, the controller is configured to control the heater to cool the annealed component to a first temperature at a first rate, and to cool the annealed component to a second temperature at a second rate. The second temperature is less than the first temperature. The first rate is slower than the second rate.

[0099] In still other features, a component comprises a first subcomponent and a second subcomponent. The first and second subcomponents are made of a material having a crystalline structure. The second subcomponent is bonded to the first subcomponent. A joint between the first and second components includes a grain boundary.

[0100] In another feature, the material includes a single crystalline structure.

[0101] In another feature, the material includes a multicrystalline structure.

[0102] In another feature, the joint includes a powder of the material before the second subcomponent is bonded to the first subcomponent, and the joint includes a plurality of the grain boundary after the second subcomponent is bonded to the first subcomponent.

[0103] In another feature, the joint does not include a powder of the material before the second subcomponent is bonded to the first subcomponent, and the joint includes a plurality of the grain boundary after the second subcomponent is bonded to the first subcomponent.

[0104] Further areas of applicability of the present disclosure will become apparent from the detailed description, the claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0105] FIG. **1**A shows an example of a graph for extraction kinetics of various materials, indicating removal efficiency of the materials as a function of temperature, for each of various elements commonly found in silicon;

[0106] FIG. **1**B shows another example of a graph for extraction kinetics of various materials, indicating removal efficiency of the materials as a function of melting time, for each of various elements commonly found in silicon;

[0107] FIG. **2** shows an example of an e-beam system used to generate silicon vapor by heating a silicon boule;

[0108] FIG. **3** shows an example of a graph depicting a calculated maximum temperature of a top face of the silicon boule of FIG. **2** as a function of electron beam power;

[0109] FIG. **4** shows an example of an e-beam system to perform a continuous melting operation of silicon;

[0110] FIGS. **5**A through **5**C show exemplary embodiments of a system used for direct melting of silicon powder and a silicon block by e-beam melting;

[0111] FIG. **6** shows an example of a system to produce 3D components by e-beam-based additive manufacturing using high-purity silicon powders;

[0112] FIG. **7** shows an example of a graph showing silicon temperature as a function of time used to determine an appropriate build temperature for the silicon in accordance with various embodiments of the disclosed subject matter;

[0113] FIG. **8**A shows an exemplary embodiment of a flow chart for preparing high-purity silicon powders in accordance with various embodiments; and

[0114] FIG. **8**B shows an exemplary embodiment of a flow chart for forming three-dimensional (3D) components from silicon in a layer-by-layer process in accordance with various embodiments.

[0115] The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0116] FIG. **9**A shows an example of a substrate processing system comprising a processing chamber;

[0117] FIG. **9**B shows an example of an electron beam generator providing an electron beam to a vacuum chamber for building a component using electron beam melting (EBM);

[0118] FIGS. **10**A-**10**C show a powder bed based system for printing fully dense silicon materials on substrates according to the present disclosure;

[0119] FIG. **10**D shows a system for selecting powders of nonmetallic materials for printing components using the systems and methods of the present disclosure;

[0120] FIG. **10**E shows a system for manufacturing spherical shape, dense and doped powder of a material such as silicon using plasma rotating electrode processing (PREP);

[0121] FIG. **10**F shows a system for manufacturing spherical shaped, dense, and doped powder of a material such as silicon using atmospheric pressure inductively coupled thermal plasma (ICTP);

[0122] FIG. **10**G shows a temperature profile of a process performed by the system of FIG. **10**F;

[0123] FIGS. **11**A and **11**B show a powder bed based method for printing fully dense nonmetallic materials on substrates according to the present disclosure;

[0124] FIGS. **12**A and **12**B show a powder bed based system for printing fully dense and crack free nonmetallic materials on nonmetallic substrates according to a high temperature powder bed method of the present disclosure;

[0125] FIG. **12**C shows a powder bed based method for printing fully dense and crack free nonmetallic materials on nonmetallic substrates according to the high temperature powder bed method of the present disclosure;

[0126] FIGS. **13**A-**15**B show various systems and methods for bonding and repairing silicon components using electron beam melting (EBM) according to the present disclosure; and

[0127] FIGS. **16**A-**16**C show bonding of two silicon components using the systems and methods of FIGS. **13**A-**13**C, **15**A, and **15**B resulting in a grain boundary between the two components due mismatched crystalline orientation.

[0128] In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

[0129] The description that follows includes illustrative examples, devices, and apparatuses that embody various aspects of the disclosed subject matter. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide an understanding of various embodiments of the inventive subject matter. It will be evident however, to those of ordinary skill in the art, that various embodiments of the disclosed subject matter may be practiced without these specific details. Further, well-known structures, materials, and techniques have not been shown in detail, so as not to obscure the various illustrated embodiments. As used herein, the terms "about" or "approximately" may refer to values that are, for example, within ±10% of a given value or range of values.

[0130] In various embodiments described herein, solutions to form 3D components (e.g., parts) from silicon use additive-manufacturing methods and additive-manufacturing tools to print the component layer-by-layer. Such methods and tools provide a highly precise and accurate final component. In embodiments, the disclosed subject matter uses a high-power beam, such as that emitted by an electron-beam (e-beam generator (gun)) or laser, to melt silicon powder and make silicon components in the aforementioned layer-by-layer manner to a near-net shape. In various embodiments employing the e-beam generator, the disclosed subject matter includes a powder-bed apparatus to assist in forming the printed components. The powder-bed apparatus is described in detail below.

[0131] As described in more detail below, because of the brittle nature of silicon materials, the ambient temperature for 3D silicon-based printing is generally performed at greater than about 1000° C. to prevent stress buildup and cracking. In some embodiments, the 3D silicon-based printing is generally performed at greater than about 1200° C. The 3D printed material may also be cooled slowly, also to prevent residual stresses and cracking.

[0132] In various embodiments, a temperature may be chosen that is above the temperature of a ductile-to-brittle transition temperature of silicon, as will be recognized by a person of ordinary skill in the art. The skilled artisan will further recognize that silicon is a brittle material at low temperatures, at which temperatures the silicon can shatter. Brittle materials can shatter due to stresses generated during rapid transitions from high temperatures to low temperatures. However, at elevated temperatures, the behavior of silicon changes. After a transition temperature is reached, silicon suddenly becomes ductile, much like many metallic materials. As is also explained in more detail below, the printed silicon components retain fewer residual stresses and fewer or no cracking issues occur if the printed silicon component is cooled down slowly, at a controlled and pre-determined rate, from the printing temperature of the silicon component.

[0133] Due to silicon high reactivity (especially when the silicon is melted) with an atmospheric ambient, such as oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), and other reactive gases, the disclosed subject matter performs silicon-printing operations in vacuum or in an inert gas (e.g., argon (Ar) or helium (He)). As is also described in more detail below, a substrate on which the silicon component is printed may also comprise silicon, Printing silicon-on-silicon reduces or avoids a coefficient-of-thermal-expansion (CTE) mismatch between materials. Further, employing a silicon substrate over substrates comprising other materials, such as metals, also helps to minimize or avoid contamination due to impurity diffusion from the non-silicon material into the printed silicon component. Effects of impurity diffusion increase at the high temperatures used during printing and annealing.

[0134] In various embodiments, the silicon powder used in the 3D printing process uses, for example, a fluidized-bed chemical vapor deposition (CVD) process. Silicon particles used in this process have a generally granular shape with a median size of approximately 50 μm and a distribution range between about 10 μm to about 100 μm. In embodiments, the purity of CVD silicon powder is generally greater than about 99.99%. In some embodiments, the purity of CVD silicon powder is generally greater than about 99.9999%. In embodiments, the silicon powder is baked in a range of about 700° C. (e.g., in a range of 650° C. to 750° C.) under high vacuum (e.g., about 10^{-6} Torr or in a range of 10^{-5} Torr to 10^{-7} Torr) to decompose and remove surface oxide (e.g., native oxide) before use of the silicon powder. The silicon powder used can be processed with a purity of greater than about 99.99% by various techniques described herein.

[0135] In various embodiments, and as described in more detail below, one 3D printing technology of the disclosed subject matter is powder-bed-based using an electron beam to melt the silicon powder. The silicon printing is performed layer-by-layer on a substrate, as described above. However, in contrast to 3D printing of metal-based materials, the systems and methods of the various embodiments of the disclosed subject matter consider other factors that affect printing quality when using silicon. Further, the disclosed subject matter includes, for example, a discussion of considerations involving particle morphology (e.g., substantially spherical particles versus other geometric forms, such as variants of polygonal volumes), as well as particle sizes and size ranges, and a distribution of the size ranges of the silicon powder.

[0136] Therefore, various embodiments of the disclosed subject matter can be highly generalized as three-step process: (1) form high-purity silicon; (2) prepare silicon powders from the high-purity silicon; and (3) use a 3D printing process employing the silicon powders. Each of these steps is explained in greater detail below in the form of exemplary embodiments.

[0137] FIG. **1**A shows an example of a graph **100** for extraction kinetics of various materials, indicating removal efficiency of the materials as a function of temperature, for each of various elements commonly found in silicon. The graph is based on a theoretical removal flux that assumes a perfect vacuum and that the impurity concentration follows Henry's law. As is known to a skilled artisan, Henry's Law, states that, at a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is proportional to its partial pressure in the gas phase. Consequently, Henry's law can therefore determine a mole fraction of a gas at a given time, t, versus the initial mole fraction at a given temperature.

[0138] The graph **100** of FIG. **1**A therefore shows the removal efficiency for various elements to be extracted from, for example, a metallurgical-grade silicon (MG-Si) at a given temperature. High vapor-pressure impurities in, for example, MG-Si, are removed by vacuum during electron-beam melting. Impurities generally need to have a higher vapor pressure than silicon (which is about 1.6×10^{-3} Torr (approximately 0.21 Pa) at 1500° C.). Many of these elements are commonly found in Si. A vapor pressure at a given temperature may be found readily in the art for each of these elements.

[0139] The elements shown in the graph include phosphorus (P), calcium (Ca), aluminum (Al), magnesium (Mg), iron (Fe), and boron (B). Consequently, for example, Ca asymptotically approaches 100% removal efficiency at about 1750 K and Mg asymptotically approaches 100% removal efficiency at about 2100 K. For the 3D-printed components formed from the processes described herein, a high-purity Si is typically used. However, as will be described in more detail below with reference to FIGS. **5**A through **5**C, there are advantages to using a more conductive version of Si (as compared with intrinsic Si). Therefore, some boron, which is not efficiently removed by an increased temperature alone, can actually be advantageous in that it allows the silicon to be more conductive than intrinsic silicon, thereby reducing or preventing a charge accumulation on silicon powders.

[0140] An electron-beam (e-beam) generator described below with reference to FIGS. **2**, **4**, and **5**A through **5**C may be employed to provide sufficient energy to raise the temperature of an MG-Si or EG-Si sample to at or above the temperatures shown. As is known in the art, intrinsic Si melts at about 1414° C. (approximately 1687 K) and has a boiling point of about 3265° C. (approximately 3538 K), both temperatures are given at atmospheric pressure (about 760 Torr or about 101.3 kPa).

[0141] FIG. **1**B shows another example of a graph **130** for extraction kinetics of various materials, indicating removal efficiency of the materials as a function of melting time (in kiloseconds, ks) for each of various elements commonly found in silicon as described above. As is indicated by the graph, Ca asymptotically approaches 100% removal efficiency after about 0.75 ks (750 seconds), whereas Mg has only about a 95% removal after 7 ks.

[0142] FIG. **2** shows an example of an e-beam system **200** that may be used to generate silicon vapor by heating a silicon boule **235**. As described above with reference to FIGS. **1**A and **1**B, the heating effect from an axially-mounted, e-beam generator **251** can be used to remove most or all impurities from the silicon boule **235** (e.g., an MG-Si boule). FIG. **2** is shown to include a substrate load portion **210**, a pre-treatment portion **220**, and a silicon-deposition portion **230**.

[0143] The substrate load portion **210** may comprise an inert-gas (e.g., an argon (Ar) or helium (He)) environment in which a load-lock chamber **211** provides an entry point for a substrate **222** into the e-beam system **200**. In a specific exemplary embodiment, the substrate **222** comprises silicon (e.g., a silicon wafer). After the substrate **222** is loaded, an entirety of the e-beam system **200** may be evacuated to a pre-determined vacuum level (e.g., 10-6 Torr or some other level to provide a desired level of vacuum for operation of the e-beam generator **251** and deposition of Si particles onto the substrate **222**, as explained below).

[0144] As the substrate **222** continues along a path within the e-beam system **200**, the substrate **222** may be heated by a, for example, backside radiation heater **221** or other type of radiant heater known in the art. The substrate **222** may be heated to, for example, 50° C. to 200° C. or higher.

[0145] As shown, a negative bias voltage is applied to the substrate **222** as the substrate traverses a plasma volume **227** generated by, in this embodiment, a hollow-cathode, arc-discharge plasma generator **225**. A noble, ultra-pure gas (e.g., Ar) is delivered **223** to the plasma generator **225** to create gaseous ions (in this case, Ar ions). The gaseous ions in the plasma volume **227** are accelerated to the substrate **222** in the pre-treatment portion **220** by the bias voltage applied to the substrate **222**.

[0146] As is known in the art, the gaseous ions provide cleaning of the substrate **222** by a sputtering effect, thereby cleaning surface contaminants from a surface of the substrate **222** that is proximate to the plasma generator **225**. The substrate then continues into the silicon-deposition portion **230** of the e-beam system **200**.

[0147] E-beams generated by the e-beam generator **251** are deflected toward a surface of the silicon boule **235** by a strong magnetic field. The silicon boule **235** is mounted within a quartz radiation-shield **233**. The e-beam is regulated to provide a slow heating level of the silicon boule **235** up to a brittle-to-ductile transition temperature of silicon, or higher, to reduce or prevent cracking. In a specific exemplary embodiment, a temperature ramp-rate of about 50 K per minute may be used to reduce or prevent cracking. At this temperature ramp-rate, a temperature of approximately 800° C. (about 1073 K) can be achieved in approximately 15.5 minutes. In various embodiments, the ramp rate be determined by, for example, finite-element analysis comparing heat flux and induced mechanical stresses. An uppermost surface of the silicon boule **235** begins to melt, producing a cloud of Si vapor **231**, which is then deposited on the substrate **222** once the substrate **222** is moved into position over the silicon boule **235**. The Si particles are deposited onto the substrate **222** by a physical vapor deposition process. A thickness of the deposited Si onto the substrate is determined by a pre-determined time in which the substrate remains over the silicon boule **235** and within the cloud of Si vapor **231**.

[0148] After an entirety of the silicon boule **235** reaches the brittle-to-ductile transition temperature, rapid heating occurs to the melt temperature of the silicon. The brittle-to-ductile transition temperature may be estimated by measured temperatures at several locations along the silicon boule **235**, combined with a finite-element simulation.

[0149] Once removed from the e-beam system **200**, the silicon coating (which may be formed as a crystalline layer over the substrate **222**) that was deposited on the substrate **222** may be removed from the substrate **222**. The substrate **222** may then be reused within the e-beam system **200**.

[0150] With reference now to FIG. **3**, an example of a graph **300** depicting calculated maximum temperature of a top face of the silicon boule **235** of FIG. **2** is shown as a function of electron beam power. In this example, a desired thermal equilibrium temperature at steady state of about 1000° C. (approximately 1273 K) is reached with about 3 kW of power input to the silicon. Recall that various embodiments of the disclosed subject matter use a temperature of about 1000° C. brittle-to-ductile transition temperature of silicon to reduce or prevent cracking. As shown in FIG. **3**, the maximum temperature rises nearly linearly with increased e-beam power up to about 5 kW. Above 5 kW for the embodiment depicted by FIG. **2**, thermal losses from radiation and evaporation become dominant and the slope of the curve of temperature as a function of e-beam power changes.

[0151] FIG. **4** shows an example of an e-beam system **400** to perform a continuous melting operation of silicon. The e-beam system **400** is shown to include a vacuum chamber **406**, a silicon-powder feed hopper **403**, a sensor **401** to monitor a mass of silicon powder **405** leaving the feed hopper **403**, a cooled crucible **409** (e.g., a water-cooled copper crucible in one specific exemplary embodiment), an input cooling-line **4111** and an output cooling-line **4110**, an observation port **404**, a pump **417** to evacuate the vacuum chamber **406** (e.g., down to approximately 10^{-6} Torr or to some pre-determined level of vacuum) an e-beam generator **413** to produce an electron beam **407**, and an e-beam controller **415**. The e-beam generator **413** may be the same as or similar to the e-beam generator **251** of FIG. **2**. In a specific exemplary embodiment, the e-beam generator **413** can supply up to 300 kW of power. However, as noted above, the e-beam generator **413** is controlled by the e-beam controller **415** to heat the silicon powder **405** slowly to reduce or prevent cracking of the silicon.

[0152] As the silicon powder **405** is fed into the cooled crucible **409**, the electron beam **407** melts the silicon powder **405**. In various embodiments, once the silicon powder **405** is melted and a desired mass or volume of melted silicon is collected in the crucible **409**, the crucible **409** may be cooled slowly, as described above, by transferring a cooling fluid (e.g., water) through the input cooling-line **4111** and out of the output cooling-line **4110**. Along with the cooling provided to the melted silicon by the crucible **409**, the power of the electron beam **407** emitted by the e-beam generator **413** may also be reduced slowly at a pre-determined ramp-down rate as described above. To prevent copper contamination into the silicon powder **405**, the silicon is not fully melted in the crucible **409**. The portion of the silicon powder **405** that is close to interior sidewalls of the crucible **409** will be at a temperature similar to that of the crucible **409**, thereby preventing potential copper contamination of the silicon powder **405**.

[0153] FIGS. **5**A through **5**C show exemplary embodiments of a system used for direct melting of silicon powder and a silicon block by e-beam melting. Although not shown explicitly, the embodiments of FIGS. **5**A through **5**C are carried out under vacuum, as described above. Further, various components of the system of FIGS. **5**A through **5**C may be the same as or similar to related ones of the various components described above with reference to FIG. **4**. For example, an e-beam generator **531** may be the same as or similar to the e-beam generator **413** of FIG. **4**. Also, a crucible **511** may be the same as or similar to the crucible **409** of FIG. **4**.

[0154] In this embodiment, a silicon block **513**A at operation **510** of FIG. **5**A is added to silicon powder **515**A by a direct melting process as shown at operation **530** in which the silicon block **513**A, when exposed to the e-beam generator **531**, forms a now partially-melted silicon block **513**B. The partially-melted silicon block **513**B enables continuous melting of the silicon and infiltrates into the now partially-melted silicon powder **551**B, resulting in a silicon ingot **551** at operation **550**. As with the systems of FIGS. **2** and **4** described above, various ramp-up rates and ramp-down rates of temperature are controlled to reduce or prevent cracking of the silicon ingot **551**.

[0155] Once high-purity silicon is obtained from the various methods described above, the silicon is changed into a powdered form for the printing operation by various methods. For example, silicon powder may be generated by a fluidized-bed chemical vapor deposition (FB-CVD) system using silane (SiH_4)-gas atomization processing. Silicon powder may also be generated by plasma rotation electrode processing (PREP). In FB-CVD, silane is deposited on small silicon particles. In the gas atomization process, silicon is melted under inert gas blanket or under vacuum. The molten silicon is forced through a nozzle where high-velocity helium (He) or argon (Ar) gas breaks the silicon into fine silicon particles. The gas atomization process and FB-CVD generate satellite silicon particles (e.g., powdered silicon), which affects powder flowability and therefore printing quality. In plasma rotating electrode processing, a silicon rod is used as feedstock and rotates rapidly inside a chamber. A plasma torch melts the end of silicon rod while it is in high-speed rotation. Centrifugal force ejects molten silicon from the silicon rod, where it solidifies into fine, substantially-spherical particles. This process generates high purity and substantially-uniform silicon powder particles since melting and solidification occur in inert gas environment. A morphology of the silicon particles can be adjusted by adjusting a rotational speed of the silicon rod.

[0156] FIG. **6** shows an example of a system **600** to produce 3D components by e-beam-based additive manufacturing using high-purity silicon powders. Such a system **600** that can be used with the novel silicon-powder generation techniques described herein is available from, for example, Arcam AB, Krokslätts Fabriker 27A, SE 431 37 Mölndal, Sweden.

[0157] With continuing reference to FIG. **6**, the system **600** is shown to include an electron beam (e-beam) column **610** and a 3D printing chamber **630**. A filament **611** of the e-beam column **610** generated an e-beam **647** that traverses through an astigmatism lens **613**, a focus lens **615**, and a deflection lens **617**. The astigmatism lens **613** and the focus lens **615** prepare a collimated version of the e-beam **647** that can be driven to various x-y coordinates on a substrate **641** located above a build platform **643** as described in more detail below. Since the 3D component to be printed is formed from silicon powder, the substrate **641** can also be formed from silicon to reduce or eliminate any stresses from a CTE mismatch, as described above. In various embodiments, the silicon substrate **641** may be chosen to have a desired epitaxial structure, which may be used to generate a matching epitaxy in the printed component. In other embodiments, the substrate **641** can be formed from steel, coated or uncoated, or another non-contaminating material having a CTE similar to that of silicon but having a higher melting point. However, depending upon the application, consideration should be given to whether other materials may diffuse into bulk silicon. In other embodiments, the substrate **641** may also comprise an existing silicon part or silicon component onto which additional material is to be added.

[0158] The x, y, and z coordinates are added to, for example, a computer-aided design (CAD) program, from a pre-determined CAD file, into a computer (not shown), such as a personal computer, a micro-processor, a controller, or other type of device capable of running the CAD program and driving the deflection lens **617**. Such a device will be recognizable to a person of ordinary skill in the art, upon reading and understanding the disclosed subject matter provided herein. Further, the skilled artisan will recognize that the z coordinates of the CAD file indicate a height over which the 3D component is to be formed. An executable program within the system **600** effectively “slices” the z coordinates into thicknesses that correspond to a thickness of a silicon layer to be printed. Each of the z slices is formed at a different z height by moving the substrate, as described below.

[0159] With continuing reference to FIG. **6**, the 3D printing chamber **630** includes a vacuum chamber **631**. In various embodiments, the vacuum chamber **631** may be evacuated to a level of less than, for example, about $75\cdot(10^{-6})$ Torr. In various embodiments, the vacuum chamber **631** may be evacuated to a level of less than, for example, about 10^{-5} Torr. Within the vacuum chamber **631**, one or more hoppers **633** hold the pre-loaded and pre-sized silicon powder. The silicon powder is formed into a volume above the substrate **641** and the build platform **643**. A rake **635** then moves mechanically in a horizontal direction **637** above the silicon powder that has been dropped form the one or more hoppers **633** to create a pre-determined thickness of silicon powder above the substrate **641**. As the e-beam **647** is energized and driven in x-y coordinates based on the pre-determined pattern (from the CAD file, described above), the energy from the e-beam **647** melts the silicon powder creating a pattern in silicon of the 3D component being printed, layer-by-layer. In various embodiments, a thickness of a layer may be in a range of about 30 μm to about 60 μm.

[0160] After a layer is printed, the substrate **641** is raised by the build platform **643** in a direction **645** such that subsequent layers of a 3D component being printed on the substrate **641** can be lowered from an uppermost location **639** of the powder bed after each layer is printed. The rake **635** levels a subsequent silicon powder bed deposited from the one or more hoppers **633** and the process continues until the 3D component is fabricated. Once the 3D component is completed, the power applied to the e-beam **647** may be ramped down slowly at a pre-determined ramp rate, as described above, to reduce or prevent any stress cracking the component.

[0161] In various embodiments, a power level of the e-beam **647** may be selected to be from about 50 W to about 300 W. A full-width, half maximum (FWHM) diameter of the e-beam **647** at the build platform **643** is selectable from about 200 μm up to about 10 mm. The e-beam **647** can be driven by the deflection lens **617** at a velocity of up to about 8000 meters per second (m/s). Depending on a number of factors including, for example, build material and build complexity of the printed part, the system **600** can have a built rate of from about 55 to about 80 cubic centimeters per hour (cm^3/h). Although the system **600** of FIG. **6** shows only a single e-beam, in various embodiments, up to about 100 e-beams may be generated.

[0162] In a specific exemplary embodiment, an energy density of the e-beam **647** at a surface of the build platform **643** is about 28 Joules per cubic millimeter (J/mm^3), with a diameter (e.g., spot size) of the e-beam **647** being about 100 μm, driven at a velocity of about 2.9 m/s. In other embodiments, the e-beam spot size may be from about 350 μm to about 2000 μm. The beam current may be about 30 mA for initial heating of the silicon powder with a beam current for about 5 mA to about 10 mA for final heating. Also, the substrate **641** may be heated to a temperature in a range of about 150 K to about 250 K below the melt temperature of silicon (e.g., the substrate **641** may be heated to about 1130° C.).

[0163] In various embodiments, a number of "buffer layers" of silicon may initially be printed onto the substrate **641**, followed by layers of printed silicon for the actual component. The buffer layers may be printed at a faster rate than the rate at which the subsequent silicon layers are printed on the buffer layers to print the component. Using buffer layers of silicon reduces any CTE-expansion mismatch between a non-silicon substrate **641** and the silicon layers printed on the buffer layers if the non-silicon substrate **641** is not formed from silicon or a material having a similar CTE as silicon. Without the buffer layers, a large CTE mismatch can exist between the substrate **641** and the silicon layers printed directly on the substrate **641** to print a component. The CTE mismatch can lead to potential fracture or fractures in the printed component. Printing using a buffer layer typically only applies when the non-silicon substrate **641** is used. The buffer layer consists of, for example, about 50 to about 100 layers printed at a faster rate than a subsequent normal silicon-printing. Once buffer-layer printing is completed, the silicon printing starts with a normal printing rate. If silicon substrate is used, the buffer-layer printing may be skipped.

[0164] With reference now to FIG. **7**, an example of a graph **700** showing silicon temperature **711** as a function of time is shown and is used to determine an appropriate build temperature, TB, for the silicon powder in accordance with various embodiments of the disclosed subject matter. The graph **700** indicates the temperature evolution of a fixed point in a printed component where the e-beam (e.g., the e-beam **647** of FIG. **6**) passes several times in each layer in the layer-by-layer construction of the printed component as described above with reference to FIG. **6**. The graph **700** shows a solidification temperature line **719**, a phase-transition temperature line **717**, a build temperature line **715**, and an ambient temperature line **713**.

[0165] Below the solidification temperature line **719**, the silicon begins to solidify. Above the solidification temperature line **719**, the silicon melts (the melt temperature, Tnn). A first time period **701** occurs over a time lasting from several seconds to several minutes or more, and depends at least partially upon a selected cooling ramp-down rate, a temperature to which the silicon particles are heated, and a velocity over which the e-beam passes by a given spatial point in the printed component. A second time period **705** occurs approximately after the silicon temperature **711** has passed below the phase-transition temperature line **717** up until the build temperature line **715** is reached (the build temperature, TB). The second time period **705** may continue over a period of minutes. As noted by the graph **700**, the silicon temperature **711** curve oscillates within an oscillation time period **703**. The oscillations in temperature are due to heating of adjacent regions or adjacent layers within the printed component. A third time period **707** over which the build temperature, TB, is maintained is selectable depending upon various factors chosen to perform operations to form the printed component, as described above, as well as a complexity and physical size of the build. Therefore, the third time period **707** may last several hours. After the component is fully printed, the silicon temperature **711** ramps down, depending upon the cooling ramp-down rate selected, until the ambient temperature line **713** is reached. The ambient temperature line **713** in many embodiments is considered to be at room temperature, TR (e.g., about 20° C. to about 25° C.). A fourth time period **709** over which the component cools may extend for several hours. In a specific exemplary embodiment, the descending temperature of the ramp-down rate is less than about 5° C. per minute from the build temperature, down to approximately 400° C. or lower. An inert gas (e.g., Ar or He) may then be pumped into the processing chamber.

[0166] Referring now to FIG. **8**A, an exemplary embodiment of a flow chart **800** for preparing high-purity silicon powders in accordance with various embodiments is shown. Many or all of the operations described below are made with reference to various embodiments already described above. For example, the operations of the flow charts **800** of FIG. **8**A and **830** of FIG. **8**B refer to various temperature ramp-up rates, temperature ramp-down rates, means of producing high-purity silicon, and printing various components. Each of these techniques, procedures, and associated apparatuses and system are described above. Further, as described in more detail below, one or more of the various processes and operations may be formed in an order other than what is shown explicitly within the figures. Therefore, unless otherwise stated, nothing requires that the operations necessarily be performed in the order illustrated.

[0167] With continuing reference to FIG. **8**A, at operation **801**, silicon is placed or otherwise formed within an apparatus (such as in, for example, the crucible **409** of the e-beam system **400** of FIG. **4**). The temperature of the silicon is increased at a pre-determined ramp-up rate. At operation **803**, high-purity silicon is prepared or otherwise formed in accordance with various exemplary embodiments described above (for example, with reference to one or more of FIGS. **2**, **4**, and **5**A through **5**C). Once the high-purity silicon is prepared or otherwise formed, at operation **805**, the temperature of the silicon is decreased at a pre-determined temperature ramp-rate down to, for example, ambient temperature (e.g., such as room temperature, TR, as described with reference to FIG. **7**). At operation **807**, powdered silicon is prepared or otherwise formed from the high-purity silicon. The powdered silicon is then filtered and/or sized by size and/or morphology at operation **809**. For example, the powdered silicon may be sized through the use of mechanical sieves, known in the art. However, in various embodiments, sizing and filtering processes are performed within an inert-gas environment (e.g., Ar or He) to prevent native oxide from forming on surfaces of the silicon.

[0168] FIG. **8**B shows an exemplary embodiment of a flow chart **830** for forming three-dimensional (3D) components from silicon in a layer-by-layer process in accordance with various embodiments. For example, a person of ordinary skill in the art may find that concurrent reference to FIG. **6**, and the accompanying text, may increase understanding of at least some of the operations described below with reference to FIG. **8**B.

[0169] At operation **831**, the CAD file is loaded into the printing tool (e.g., the system **600** of FIG. **6**). Filtered and/or sized powdered silicon is added into the printing tool (e.g., into the one or more hoppers **633**) at operation **833**. As noted above, in a specific exemplary embodiment, the powdered silicon is maintained in an inert-gas environment to avoid native oxide (SiO_2 or Si_xO_y) growth on the silicon particles. In certain applications, the native oxide may be considered to be a contaminant for printing certain types of 3D components from silicon.

[0170] At operation **835**, the powdered silicon is added into the powder bed and the powder bed is raked to form a substantially uniform layer of silicon of a pre-determined thickness. The temperature of the silicon is increased at operation **837** (e.g., by the e-beam **647** of the system **600**) at a pre-determined ramp-up rate in accordance with various embodiments described above.

[0171] If buffer layers are desirable (e.g., when using a build table, such as the substrate **641**, when the substrate is formed from a material with a CTE value not substantially matching that of silicon as described above), one or more buffer layers may optionally be printed prior to beginning printing of the actual 3D component at operation **839**. Such buffer layers may be printed onto the substrate to, for example, either mimic a lower portion of the 3D component to be printed or may alternately be printed over an entirety or near entirety of an uppermost surface of the substrate.

[0172] At operation **841**, a first layer of the 3D component is printed, either onto the substrate directly or onto the one or more buffer layers. A determination is made (for example, within the CAD program) at operation **843** as to whether all layers of the silicon component have been printed. If all layers have been printed, the component is cooled at the pre-determined ramp-down rate of temperature to, for example, ambient temperature, at operation **845**. The silicon component is removed from the printing tool and then separated from the substrate at operation **847**.

[0173] If at operation **843**, a determination has been made that not all layers have been printed, the flow chart **830** continues to the print layer of component at operation **841**.

[0174] The following numbered examples are specific embodiments of the disclosed subject matter.

[0175] Example 1: A method of performing three-dimensional (3D) printing of a silicon component, the method including adding powdered silicon to a 3D printing tool. For each layer of the 3D printing in a layer-by-layer process: forming a powder bed of the powdered silicon in the 3D printing tool, baking the powdered silicon in a temperature range of 650° C. to 750° C. under a high-vacuum condition in a range of 10^{-5} Torr to 10^{-7} Torr to decompose and remove surface oxides from the powdered silicon, forming a layer of the powder bed to a pre-determined thickness, directing a high-powered beam under the high-vacuum condition in a pre-determined pattern into the formed powder-bed, the high-powered beam having sufficient energy to melt the powdered silicon, and making a determination as to whether additional layers in the 3D printing are needed. Based on a determination that no additional layers are needed, cooling the silicon component at a pre-determined temperature ramp-down rate to about ambient temperature of an environment in which the 3D printing tool is located.

[0176] Example 2: The method of example wherein the high-powered beam comprises an electron beam.

[0177] Example 3: The method of any one of the preceding Examples, wherein the method is performed within an inert gas environment.

[0178] Example 4: The method of Example 3, wherein the inert gas environment comprises at least one gas selected from gases including argon (Ar) and helium (He).

[0179] Example 5: The method of any one of the preceding Examples, wherein silicon particles in the silicon powder have a median size in a range of about 45 μm to about 55 μm and a distribution range of sizes between about 10 μm to about 100 μm.

[0180] Example 6: The method of any one of the preceding Examples, wherein a purity of the powdered silicon is generally greater than about 99.99%.

[0181] Example 7: The method of any one of the preceding Examples, wherein a purity of the powdered silicon is generally greater than about 99.9999%.

[0182] Example 8: The method of any one of the preceding Examples, wherein the powdered silicon is baked in a temperature range of about 700° C. under a high-vacuum condition in a range of about 10-6 Torr to decompose and remove surface oxides from the powdered silicon.

[0183] Example 9: The method of any one of the preceding Examples, wherein the powdered silicon comprises substantially spherical particles.

[0184] Example 10: The method of any one of the preceding Examples, wherein the powdered silicon is formed by a fluidized-bed chemical vapor deposition (FB-CVD) system using silane (SiH_4)-gas atomization.

[0185] Example 11: The method of Example 10, further including preparing molten silicon, forcing the molten silicon through a nozzle, directing a high-velocity gas stream at the molten silicon, the high-velocity gas stream comprising at least one gas selected from gases including helium (He) and argon (Ar) to break the molten silicon into silicon particles to form the powdered silicon, and depositing silane on the silicon particles.

[0186] Example 12: The method of any one of the preceding Examples, wherein the powdered silicon is formed by plasma rotation electrode processing (PREP).

[0187] Example 13: The method of Example 12, further including melting an end of a silicon rod while the silicon rod is rotated, a rotational speed of the silicon rod being sufficient to create a centrifugal force to eject molten silicon from the silicon rod, and solidifying the ejected molten silicon into silicon particles to from the powdered silicon.

[0188] Example 14: The method of Example 13, further including adjusting a morphology of the silicon particles by adjusting the rotational speed of the silicon rod.

[0189] Example 15: The method of any one of the preceding Examples, wherein the pre-determined temperature ramp-down rate is less than about 5° C. per minute.

[0190] Example 16: The method of any one of the preceding Examples, further including preparing high-purity silicon by operations including: placing silicon into a crucible, increasing a temperature of the silicon at a pre-determined ramp-up rate, at least partially melting the silicon with high-powered beam, the high-powered beam having a power sufficient to melt the silicon, and decreasing the temperature of the silicon at a second pre-determined ramp-down rate.

[0191] Example 17: The method of Example 16, wherein the pre-determined ramp-up rate of temperature is determined by finite-element analysis including comparing heat flux and induced mechanical stresses in the silicon.

[0192] Example 18: The method of Example 16, wherein the temperature ramp-rate is about 50 K per minute.

[0193] Example 19: The method of any one of the preceding Examples, wherein the pre-determined thickness of each layer in the layer-by-layer process is within a range from about 30 μm to about 50 μm.

[0194] Example 20: A method of performing three-dimensional (3D) printing of a silicon component, the method including loading a design file into a 3D printing tool where the design file containing geometries of the silicon component including coordinates for each of multiple layers to print the silicon component. For each layer of the 3D printing of the silicon component: forming a powder bed of powdered silicon in the 3D printing tool, baking the powdered silicon in a temperature range of 650° C. to 750° C. under a high-vacuum condition in a range of 10^{-5} Torr to 10^{-7} Torr to decompose and remove surface oxides from the powdered silicon, raking a layer of the powder bed to a pre-determined thickness, directing an electron beam under the high-vacuum condition in a pre-determined pattern into the raked powdered-bed, the pre-determined pattern being based on the design file, the electron beam having sufficient energy to melt the powdered silicon, and making a determination as to whether additional layers in the 3D printing are needed. Based on a determination that no additional layers are needed, cooling the silicon component at a pre-determined temperature to about ambient temperature in which the 3D printing tool is located.

[0195] Example 21: The method of Example 20, wherein the design file is a computer-aided design file.

[0196] Example 22: The method of any one of the preceding Examples 20 et seq., wherein silicon particles in the silicon powder have a median size of approximately 50 μm and a distribution range of sizes between about 10 μm to about 100 μm.

[0197] Example 23: The method of any one of the preceding Examples 20 et seq., wherein a purity of the powdered silicon is generally greater than about 99.99%.

[0198] Example 24: The method of any one of the preceding Examples 20 et seq., wherein a purity of the powdered silicon is generally greater than about 99.9999%.

[0199] Example 25: The method of any one of the preceding Examples 20 et seq., wherein the powdered silicon is baked at about 700° C. under high vacuum condition of about 10-6 Torr to decompose and remove surface oxides from the powdered silicon.

[0200] Example 26: The method of any one of the preceding Examples 20 et seq., wherein the powdered silicon comprises substantially spherical particles.

[0201] Example 27: The method of any one of the preceding Examples 20 et seq., wherein a power level of the electron beam is in a range from about 50 W to about 300 W.

[0202] Example 28: The method of any one of the preceding Examples 20 et seq., wherein a full-width, half maximum (FWHM) diameter of the electron beam at a build platform upon which the silicon component is being formed is in a range from about 200 μm up to about 10 mm.

[0203] Example 29: The method of any one of the preceding Examples 20 et seq., wherein an energy density of the electron beam at a surface of the build platform is about 28 Joules per cubic millimeter (J/mm^3).

[0204] Various components used in substrate processing systems and processing chambers are manufactured with high precision. Some of these components are made of metals while others are made of materials such as silicon and ceramics. An example of a substrate processing system and a processing chamber is shown and described below with reference to FIG. **9**A to provide examples of these components and the harsh electrical, chemical, and thermal environments in which these components operate. The present disclosure relates to systems and methods for printing these components using electron beam melting (EBM).

[0205] The remainder of the present disclosure is organized as follows. Initially, an example of a substrate processing system including a processing chamber is shown and described with reference to FIG. **9**A. An example of an electron beam generator is shown and described with reference to FIG. **9**B. Subsequently, an overview of the systems and methods for 3D printing of silicon components according to a fully dense printing method and a crack free printing method is provided. Thereafter, systems and methods for 3D printing of fully dense silicon components according to the fully dense printing methods are described with reference to FIG. **10**A-**11**B. Further, systems and methods for 3D printing of fully dense and crack free silicon components according to the fully dense and crack free methods are described with reference to FIG. **12**A-**12**C. Finally, systems and methods for bonding and repairing silicon components using an electron gun are described with reference to FIGS. **13**A-**15**B. Finally, bonding of two silicon components using the systems and methods of FIGS. **13**A-**13**C, **15**A, and **15**B resulting in a grain boundary between the two components due mismatched crystalline orientation is shown and described with reference to FIGS. **16**A-**16**C.

[0206] FIG. **9**A shows an example of a substrate processing system **1100** comprising a processing chamber **1102**. While the example is described in the context of plasma enhanced chemical vapor deposition (PECVD), the teachings of the present disclosure can be applied to other types of substrate processing such as atomic layer deposition (ALD), plasma enhanced ALD (PEALD), CVD, or other processing including etching processes. The system **1100** comprises the processing chamber **1102** that encloses other components of the system **1100** and contains an RF plasma (if used). The processing chamber **1102** comprises an upper electrode **1104** and an electrostatic chuck (ESC) **1106** or other substrate support. During operation, a substrate **1108** is arranged on the ESC **1106**.

[0207] For example, the upper electrode **1104** may include a gas distribution device **1110** such as a showerhead that introduces and distributes process gases. The gas distribution device **1110** may include a stem portion including one end connected to a top surface of the processing chamber **1102**. A base portion of the showerhead is generally cylindrical and extends radially outwardly from an opposite end of the stem portion at a location that is spaced from the top surface of the processing chamber **1102**. A substrate-facing surface or faceplate of the base portion of the showerhead includes a plurality of holes through which vaporized precursor, process gas, or purge gas flows. Alternately, the upper electrode **1104** may include a conducting plate, and the process gases may be introduced in another manner.

[0208] The ESC **1106** comprises a baseplate **1112** that acts as a lower electrode. The baseplate **1112** supports a heating plate **1114**, which may correspond to a ceramic multi-zone heating plate. A thermal resistance layer **1116** may be arranged between the heating plate **1114** and the baseplate **1112**. The baseplate **1112** may include one or more channels **1118** for flowing coolant through the baseplate **1112**.

[0209] If plasma is used, an RF generating system **1120** generates and outputs an RF voltage to one of the upper electrode **1104** and the lower electrode (e.g., the baseplate **1112** of the ESC **1106**). The other one of the upper electrode **1104** and the baseplate **1112** may be DC grounded, AC grounded, or floating. For example only, the RF generating system **1120** may include an RF generator **1122** that generates RF power that is fed by a matching and distribution network **1124** to the upper electrode **1104** or the baseplate **1112**. In other examples, the plasma may be generated inductively or remotely.

[0210] A gas delivery system **1130** includes one or more gas sources **1132-1**, **1132-2**, . . . , and **1132**-N (collectively gas sources **1132**), where N is an integer greater than zero. The gas sources **1132** are connected by valves **1134-1**, **1134-2**, . . . , and **1134**-N (collectively valves **1134**) and mass flow controllers **1136-1**, **1136-2**, . . . , and **1136**-N (collectively mass flow controllers **1136**) to a manifold **1140**. A vapor delivery system **1142** supplies vaporized precursor to the manifold **1140** or another manifold (not shown) that is connected to the processing chamber **1102**. An output of the manifold **1140** is fed to the processing chamber **1102**.

[0211] A temperature controller **1150** may be connected to a plurality of thermal control elements (TCEs) **1152** arranged in the heating plate **1114**. The temperature controller **1150** may be used to control the plurality of TCEs **1152** to control a temperature of the ESC **1106** and the substrate **1108**. The temperature controller **1150** may communicate with a coolant assembly **1154** to control coolant flow through the channels **1118**. For example, the coolant assembly **1154** may include a coolant pump, a reservoir, and one or more temperature sensors (not shown). The temperature controller **1150** operates the coolant assembly **1154** to selectively flow the coolant through the channels **1118** to cool the ESC **1106**. A valve **1156** and pump **1158** may be used to evacuate reactants from the processing chamber **1102**. A system controller **1160** controls the components of the system **1100**.

[0212] As can be appreciated, the components used in substrate processing systems and processing chambers (e.g., showerheads) need to be manufactured with high precision. Some of these components are made of metals while others are made of materials such as silicon and ceramics. As explained below, 3D printing of components made of materials such as silicon and ceramics is very challenging due to their brittle nature which causes cracks using conventional 3D printing systems, and the present disclosure provides a solution for addressing the challenges and for 3D printing of fully dense and crack free components made of materials such as silicon and ceramics.

[0213] Before explaining the fully dense printing method and the crack free printing method of the present disclosure, a brief overview of electron beam melting (EBM) used in these printing methods is provided for completeness. EBM is a type of additive manufacturing or 3D printing process. A raw material in powder form is placed under a vacuum and is fused together into a solid mass using an electron beam as a heat source. Components can be manufactured by melting the powder layer by layer with the electron beam in a chamber under high vacuum. Since printing is performed at high-vacuum environment, a contamination-free work zone is provided. Additionally, using vacuum makes the process suitable for printing components of reactive materials as well (e.g., materials with a high affinity for oxygen; e.g., titanium). For the electrons to interact, the powder needs to be conductive. At temperatures >450° C., silicon becomes a good conductor. Molten silicon is also a good conductor. Therefore, EBM can be used to print silicon components using the methods of the present disclosure described below.

[0214] FIG. **9**B schematically shows an example of an electron beam generator (also called an electron gun) **1170** that is connected to a vacuum chamber **1172**. Detailed examples of the vacuum chamber and other elements used with the printing methods of the present disclosure are shown and described with reference to FIGS. **10**A-**12**C. FIG. **9**B focuses on the electron gun. The electron gun **1170** comprises a tungsten filament **1174** that is heated in a vacuum to produce electrons. Using a focus coil **1176** and a deflection coil **1178**, the electrons are accelerated and projected as an electron beam **1179** on a layer of powder **1180** deposited on a build plate **1182**. The electrons in the electron beam **1179** heat and melt the layer of powder **1180** to build a component layer by layer. A plate movement assembly **1184** lowers the build plate **1182** as the layers of the component are built. A vacuum pump **1186** maintains a high vacuum in the vacuum chamber **1172**. For example, the pressure in the vacuum chamber **1172** can be <1E-5 Torr, which is the same as <0.01 mTorr or <1.33 mPa. A power supply **1188** supplies power to the filament **1174** and the focus and deflection coils **1176**, **1178**. A controller **1190** controls the power supply **1188**, the vacuum pump **1186**, and the plate movement assembly **1184**.

[0215] Briefly, in the fully dense printing method, the present disclosure describes systems and methods for printing fully dense silicon components using 3D printing technology (i.e., additive manufacturing). The 3D printing technology of the present disclosure is powder bed based electron beam melting (EBM) that uses an electron beam to melt silicon powder on a build plate (i.e., a building platform or a substrate) in a vacuum chamber. Unlike 3D printing of metal-based materials, the systems and methods of the present disclosure address factors that affect printing quality when printing fully dense silicon components. The present disclosure describes particle morphology, size, and distribution of silicon powder and also describes a printing strategy, an appropriate electron beam power and printing speed, and a powder bed preheating strategy. All of these techniques contribute to printing fully dense silicon components using 3D printing. The systems and methods of the present disclosure can print large silicon components with complex internal features which cannot be accomplished using traditional subtractive machining methods.

[0216] Additionally, in the crack free printing method, the present disclosure describes a design of a 3D printing equipment with a low temperature gradient. The design uses one or multiple heaters along with good thermal insulation in a vacuum chamber to minimize a temperature gradient during printing of a silicon component, in-situ annealing, and cooling. Using the heaters and the insulation, a uniform high temperature with a low thermal gradient is maintained throughout the equipment and throughout the printing process. The heaters can be either resistive or inductive heaters, IR lamp radiation heaters, or blue light heaters (e.g., using blue LEDs). The insulation material can be rigid carbon fiber insulation, soft graphite felt, or a combination of both. Due to high reactivity of carbon and melted silicon with oxygen at elevated temperatures, the equipment needs to be vacuum tight. Silicon is preferably printed in a vacuum chamber under high vacuum.

[0217] The low thermal gradient method according to the crack free printing method can be used for powder bed based printing methods. Due to the brittle nature of silicon materials, the substrate temperature for 3D printing is preferably greater than the ductile to brittle transition temperature (DBTT) of silicon (e.g., >1000° C.) during printing and annealing of the silicon component to prevent thermal stress buildup. This way, silicon is ductile during printing. The printed component is also preferably cooled slowly at a controlled rate.

[0218] In the low thermal gradient method according to the crack free printing method, silicon is a preferred substrate for 3D printing of silicon components to avoid a mismatch of coefficient of thermal expansion (CTE), which can occur if non-silicon substrates are used, and which can lead to component cracking. Silicon is the preferred substrate over substrates of other material such as metals for an additional reason: to prevent contamination due to impurity diffusion from the non-silicon material into silicon, which can occur at high temperatures using during printing and annealing. Accordingly, using the crack free method of the present disclosure, silicon components with high purity and low thermal stress (e.g., crack free) can be printed. The crack free printing methodology of the present disclosure can be applied to other brittle materials such as alumina, silicon carbide, ceramics, and so on.

[0219] More specifically, the fully dense printing method addresses the following concerns for 3D printing of silicon. Current additive manufacturing technology for silicon is based on direct energy deposition (DED). Voids or pores exist in the printed silicon samples due to insufficient laser energy density or strong spatter ejection in the current laser-based printing process.

[0220] Accordingly, the fully dense printing method of the present disclosure describes using a steel substrate since a silicon substrate can crack and chip due to the thermal impact applied to the substrate during printing. The cracks can propagate in Z direction which may fracture the printed sample. A steel substrate is used to avoid the damage to the printed silicon sample. Since the melting point of steel is higher than that of silicon, steel does not melt during silicon printing.

[0221] Additionally, in the fully dense printing method, a plurality of buffer layers of silicon are initially printed on the steel substrate, and then layers of silicon for the actual component are printed on top of the buffer layers. The buffer layers are printed at a faster rate than the rate at which the subsequent silicon layers are printed on the buffer layers to print the component. This reduces a coefficient of thermal expansion (CTE) mismatch between the steel substrate and the silicon layers printed on the buffer layers. Without the buffer layers, a large CTE mismatch can exist between the steel substrate and the silicon layers printed directly on the steel substrate to manufacture a component, which can lead to fracture in the printed component. The buffer layers reduce CTE mismatch that can occur between the steel substrate and the silicon layers printed to build the component if the layers are printed directly on the steel substrate without the intervening buffer layers.

[0222] Further, in the fully dense printing method, the silicon layers are printed on the buffer layers using a double printing method as follows. Each silicon layer printed on the buffer layer is printed twice (i.e., using two passes). In a first printing or pass, the layer is printed at a faster speed (i.e., with a shorter exposure time of the electron beam) using a lower power electron beam than the speed and power used in a second printing or pass. During the first printing, the lower power does not fully melt the silicon but binds the silicon particles together. Subsequently, during the second printing, the slower speed and higher power of the electron beam scanning the material from the first pass with a longer exposure time fully melts the already bonded silicon particles from the first pass, thus forming a fully dense layer of silicon. Thus, the first printing pass can be called a sintering pass, and the second printing pass can be called a melting pass.

[0223] Furthermore, in each layer, the orientation of the electron beam in the first pass can be different than in the second pass to even out thermal stress in each layer. For example, suppose three layers A, B, and C are to be printed, and each layer is printed using two passes P**1** and P**2**. Let m and n respectively denote the angle or orientation of the electron beam in degrees during passes P**1** and P**2** in the X-Y plane along the substrate. For layer A, (m, n)=(0, 90); for layer B, (m, n)=(45, −45); and for layer C, (m, n)=(90, 0). The pattern is repeated for subsequent layers. This effectively reduces thermal stress across the layers and prevents the cracking in the printed component.

[0224] The double printing method of the first solution also reduces spatter ejection, which typically involves bright (melted airborne) particles of silicon blown away from the melting pool due to an inert gas typically flowing at the bottom of the printing chamber.

[0225] These particles cool down in flight and land on the downwind printed sample. These particles might not be fully melted during the printing of the next layer, which can cause voids or porosity in the component printed using traditional printing methods. In contrast, in the double printing method of the present disclosure, the spatter is significantly reduced since vacuum is used (i.e., no inert gas is used) during printing. Nonetheless, if any spatter occurs, the first printing pass binds these ejected particles to each other and to the silicon particles, which are then fully melted during the second printing pass. Further, since a lower power electron beam is used during the first pass, the amount of spatter ejection is reduced, and whatever spatter ejection occurs during the first pass is fully melted during the second pass.

[0226] Furthermore, any spatter ejection occurring during the second pass is also fully melted due to the use of a slow high power electron beam. Specifically, the area recently printed is still hot enough to melt any ejected particles landing in the area. Additionally, if any ejected particles land in the area to be printed, these particles are fully melted by the high power electron beam as printing continues and reaches the area. Thus, a fully dense component without porosity is manufactured using the double printing method.

[0227] In the fully dense printing method, before printing, the silicon powder is preferably filtered (i.e., sorted) using a mesh to obtain particles having size in a relatively narrow range. For example only, the range can be 40-100 μm. As another example, the range can be 50-90 μm. This ensures that the particles have spherical shape and smooth surface and that there is no particle aggregation. That is, the filtered powder flows and spreads better in the powder bed on the substrate than the unfiltered powder. When the gas atomized unfiltered powder is poured in the mesh for filtering, the filter size of the mesh is selected, and the mesh is vibrated mechanically. For example, the mesh can be vibrated mechanically or using ultrasound.

[0228] After printing, the component is separated from the steel substrate by cutting through the buffer layer, for example. The buffer layers are relatively easy to cut through, which is an additional benefit of using the buffer layers. The separated steel substrate can be refinished and prepared to receive new buffer layers to manufacture a next component.

[0229] In the fully dense printing method, due to the use of the buffer layers and the double printing method, a large CTE mismatch between the steel substrate and the printed silicon is reduced and voids in the printed silicon are eliminated. For example, while a few initial layers are being printed on the buffer layers, the buffer layers reduce CTE mismatch between the steel substrate and the layers being printed, which prevents fracturing of the printed silicon. However, a large thermal stress still exists in the printed silicon samples whenever using the fully dense printing method in the conventional metal 3D printers which do not have a high temperature hot zone. All the printed silicon samples in the conventional metal 3D printers have micro-cracks with no exception.

[0230] To eliminate the micro-cracks in the printed silicon, a new 3D printing equipment design with a low temperature gradient is described in the present disclosure. The design uses a vacuum chamber with one or multiple heaters along with good thermal insulation to minimize the temperature gradient during Si part printing, in-situ annealing, cooling. The heaters can be either resistive or inductive heaters, IR lamp radiation heaters, or blue light heaters (e.g., using blue LEDs). The insulation materials can be either rigid carbon fiber insulation or soft graphite felt or combination of both. Because of high reactivity of carbon and Si melt with oxygen at elevated temperatures, the system is enclosed in a vacuum tight environment. For example, the printing is carried out in a vacuum chamber. The low thermal gradient method can be used for powder bed based printing method.

[0231] Due to the brittle nature of silicon materials, the substrate temperature for 3D printing is preferably greater than the DBTT of silicon (e.g., >1000° C.) during printing and annealing of the silicon component to prevent thermal stress buildup. The printed component is also cooled slowly. A silicon substrate is preferred for printing silicon components to avoid CTE mismatch. The methodology can be applied to other brittle materials, such as silicon carbide (SiC), ceramics, alumina, and so on.

[0232] The new 3D printing equipment is designed for printing brittle materials, such as silicon, silicon carbide, alumina, and other ceramics. Presently, the conventional 3D printing equipment is designed for printing metals which are ductile materials and are more tolerant to thermal stress. Therefore, ex-situ annealing can be used to reduce thermal stress. However, the current 3D printing equipment is not capable of uniformly heating and maintaining high substrate temperatures (e.g., >600° C.), and large temperature gradient occurs while printing silicon components, where melt pool temperature is >1414° C., which is the melting point of silicon. In addition, the cool down in the currently used 3D printing processes is fast and not controlled. The large temperature gradient during printing and cooling down of silicon components leads to micro-cracks in all 3D-printed silicon samples using the conventional metal 3D printers (either powder bed or powder fed printing, with or without buffer layers). No crack free printed silicon samples have been observed using 3D metal printers. The micro-cracks cannot be healed in ex-situ annealing.

[0233] Accordingly, the crack free printing method of the present disclosure describes using one or multiple heaters along with good thermal insulation to minimize the temperature gradient during Si printing, in-situ annealing, and cooling. The heaters can be either resistive or inductive heaters, IR lamp radiation heaters, or blue light heaters (e.g., using blue LEDs). The insulation materials can be either rigid carbon fiber insulation or soft graphite felt or combination of both. Because of high reactivity of carbon and Si melt with oxygen at elevated temperatures, the system uses a vacuum tight chamber. For example, silicon components are printed in a vacuum chamber.

[0234] As described below with reference to FIGS. **12**A-**12**C, according to the crack free printing method, the chamber can be rectangular with rigid insulation plates covering the inside at top and bottom, left and right, front and back. Alternatively, the chamber can be cylindrical with rigid insulation plates covering the inside at top and bottom and a rigid insulation cylinder shielding the surrounding cylindrical wall. The insulation plates and cylinder can also be made of multiple layers, such as rigid insulation/rigid insulation, graphite/rigid insulation, rigid insulation/felt, graphite/felt, carbon fiber composite (CFC)/felt. Felt is essentially a cloth-like soft material made of many layers of carbon fiber. Felt prevents heat from escaping and helps in maintaining the high temperature uniform throughout the printing process (i.e., felt helps in maintaining a low thermal gradient throughout the printing process).

[0235] In the crack free silicon printing method, graphite resistive heaters are preferred and schematically laid out as shown in FIGS. **12**A-**12**C described below. One or more graphite susceptors (i.e., shields) could be placed inside the side heaters to protect the heaters. The silicon powder is dosed by a powder wiper after completion of each layer of printing. When the printing of all layers is completed, the printed samples are embedded into silicon powder. Silicon powder has low thermal conductivity and reduces heat transfer between the printed components.

[0236] Due to the brittle nature of silicon materials, the substrate temperature is preferred to be greater than the DBTT point of silicon (e.g., >1000° C.) during printing of the silicon component (so that silicon is ductile during printing) and during annealing to prevent thermal stress buildup. The annealing temperatures are preferably between 1100-1200° C. The cool down is preferably at a rate <5° C./min from annealing temperature to 400° C. and is followed by backfill of an inert gas (e.g., Ar). The substrate for 3D printing Si is preferably made of Si materials to avoid CTE mismatch and contaminations. The methodology can be used to print components of other brittle materials such as ceramics, silicon carbide, alumina, and so on.

[0237] Accordingly, by using heaters and insulation, the crack free printing method of the present disclosure maintains a low temperature gradient during printing and in-situ annealing as well as provides a slow cool down at a controlled rate, which significantly reduces thermal stress and eliminates micro-cracking in the printed Si components. In contrast, the conventional metal 3D printing equipment is not capable of maintaining temperatures above 600° C. and controlled cool down, which induces high thermal stress and causes micro-cracks in the printed Si part and renders it useless. Further, unlike the conventional metal 3D printing equipment, the printing method of the present disclosure uses a high vacuum chamber and graphite based heaters and carbon fiber based thermal insulations to minimize the temperature gradient during printing, annealing and cool down.

[0238] These and other features of the present disclosure are now described below in details. FIGS. **10**A-**11**B show the systems and methods according to the fully dense printing method of the present disclosure. FIGS. **12**A-**12**C show the system and method according to the crack free printing method of the present disclosure.

[0239] FIG. **10**A shows a system **1200** for 3D printing a component **1201** of a nonmetallic material such as silicon on a metal substrate according to the fully dense printing method of the present disclosure. The system **1200** comprises a vacuum chamber **1202**. The vacuum chamber **1202** comprises a first plate **1204** and a second plate **1206**. The first plate **1204** supports a substrate **1208** on which a component is printed. Accordingly, the first plate **1204** is also called a building plate, a building platform, a printing plate, or another suitable name.

[0240] The second plate **1206** stores the nonmetallic material **1210** (e.g., silicon powder). A dose bar or a powder wiper **1212** supplies the nonmetallic material **1210** to the substrate **1208** prior to printing each layer. Accordingly, the second plate **1206** is also called a feeding plate, a dosing plate, or another suitable name.

[0241] The vacuum chamber **1202** comprises an observation window **1214**. The observation window **1214** is coated with a film to reduce heat dissipation. The system **1200** further comprises an electron beam generator **1220** that projects an electron beam **1226** onto the substrate **1208** during printing. For example, the electron beam generator **1220** is similar to the electron beam generator **1170** shown in FIG. **9**B. Accordingly, the electron beam generator **1220** is not described in detail for brevity.

[0242] FIG. **10**B shows additional elements of the system **1200**. The system **1200** further comprises an inert gas supply **1230** to supply the inert gas to backfill the vacuum chamber **1202** after the printing is finished and before opening the vacuum chamber **1202**. The system **1200** further comprises a plate movement assembly **1232** to move the first plate **1204** downwards and to move the second plate **1206** upwards during printing. The system **1200** further comprises a vacuum pump **1218** that is connected to the vacuum chamber **1202** via a valve **1216** to maintain a high vacuum in the vacuum chamber **1202**. For example, the pressure in the chamber **1202** can be <1E-5 Torr, which is the same as <0.01 mTorr or <1.33 mPa. The system **1200** further comprises a controller **1234** that controls all the elements of the system **1200** as explained below.

[0243] For example, the system **1200** uses an electron beam melting (EBM) printing technology based printer and silicon powder manufactured by plasma rotating electrode processing (PREP, described with reference to FIGS. **10**D and **10**E below) or alternatively by inductively coupled thermal plasma (ICTP, described with reference to FIGS. **10**F and **10**G) to print silicon in a layer by layer manner. For example, a diameter of a focus spot of the electron beam **1426** may be 70 μm. The electron beam energy is delivered to a focus plane (i.e., the horizontal plane of the top surface of the build plate **1204**) via a point-by-point exposure methodology.

[0244] FIG. **10**C schematically shows how the electron beam **1226** delivers energy on the focus plane (the build plate **1204**). Each circle shown is a schematic projection of the electron beam **1226** on the focus plane and may have a diameter of 70 μm, for example. The electron beam **1226** dwells on each circle for a short time called an exposure time and then moves to a horizontally neighboring circle (next column) in a row. The moving distance is called a point distance (e.g., 80 μm) as shown in FIG. **10**C.

[0245] After completing the row, the electron beam **1226** moves to a next row. This moving distance is called a hatch distance (e.g., 60 μm) as shown in FIG. **10**C. The melting of silicon powder in each circle occurs when the electron beam **1226** is dwelling on the circle (within the exposure time). In this process, depending on the electron beam power and the exposure time, the electron beam **1226** creates a melting pool of silicon whose size is approximately 1.5-2 times the size of the circle and is about 2-3 layers deep. Therefore, the silicon powder particles are well covered by the melting pool so that they can be melted as the electron beam **1226** scans in the X-Y plane. The combination of electron beam power, exposure time, the point distance, and the hatch distance determines the energy density of the 3D printing. As this process continues, all the selected silicon powder in this layer is melted. The process continues until all the layers are completed.

[0246] In the present disclosure, the 3D printing of silicon is controlled from aspects of silicon powder, printing strategy, and thermal stress as follows. The silicon powder is manufactured via plasma rotating electrode processing (PREP) or inductively coupled thermal plasma (ICTP) method which produces silicon powder with highly spherical, dense, doped silicon particles, and which are described with reference to FIGS. **10**D-**10**G below. Each individual silicon particle has a smooth surface and does not have particle aggregation. For example, the particle size ranges between 40-100 μm. As another example, the particle size can range between 50-90 μm.

[0247] FIG. **10**D shows an example of a system **1250** for selecting silicon powder from a stock of silicon powder manufactured using PREP. The system **1250** comprises a feeder **1252** that feeds the stock of silicon powder manufactured using PREP, which is described with reference to FIG. **10**E below. The system **1250** comprises a first mesh **1254** arranged vertically above a second mesh **1256**. As shown in sections A-A and B-B of the first and second meshes **1254**, **1256**, the holes of the first mesh **1254** have a diameter d1 that is greater than a diameter d2 of the holes of the second mesh **1256**.

[0248] The feeder **1252** feeds the stock of the silicon powder manufactured using PREP into the first mesh **1254**. A vibrating system **1258** vibrates the first and second meshes

1254, **1256**. For example, the vibrating system **1258** may vibrate the first and second meshes **1254**, **1256** mechanically or using ultrasound. At the end of the sieving process carried out by the vibration, silicon powder having particles with diameters between d**1** and d**2** remain in the second mesh **1256**, which are used as the nonmetallic material **1210** for printing the component **1201**.

[0249] For example, the holes of the first mesh **1254** may be of the size 88 μm, the holes of the second mesh **1256** may be of the size 53 μm. The first mesh **1254** screens out too big particles (e.g., of size >88 μm). The second mesh **1256** screens out too small particles (e.g., of size <53 μm). The powder left in the second mesh **1256** is collected for printing. The particles in the collected powder flow smoothly without clogging the powder supply hose (not shown).

[0250] In general, it is understood that the mesh sizes can be selected depending on the particle sizes desired. For example, if the particle size is desired to be between x and y μm, where y>x, the diameter d**1** of the first mesh **1254** should be y or more (i.e., d**1**≥y), and the diameter d**1** of the first mesh **1254** should be y or more (i.e., d**1**≤x).

[0251] Accordingly, the two mesh solution may be used without constraints on how the powder stock is manufactured (i.e., the stock need not be manufactured using PREP). The single mesh solution may be used with atomized powder feed stock when any particle size less than the diameter of the mesh holes is acceptable. In general, using either solution, silicon powder having size in a relatively narrow range (e.g., 40-100 μm) can be selected for printing. As another example, using either solution, silicon powder having size in a range of 50-90 μm can be selected for printing.

[0252] FIG. **10**E shows a system **1280** for manufacturing powder of a material such as silicon using the plasma rotating electrode processing (PREP) method. The system **1280** comprises a chamber **1282**. An inert gas is circulated through the chamber **1282**. An electrode **1284** made of a material of which powder is to be manufactured (e.g., silicon) is coupled to a shaft of a motor **1286**. A plasma torch **1288** heats a distal end of the electrode **1284** to strike plasma **1290** as the motor **1286** is rotated. As a result, the distal end of the electrode **1284** melts into molten liquid. The molten liquid is crushed into droplets **1292** that are ejected by the centrifugal force of the rotating electrode **1284**. The droplets **1292** solidify into powder. The powder thus manufactured using the PREP method is used as feedstock in the systems and methods of the present disclosure.

[0253] FIG. **10**F schematically shows a system **1300** for converting an irregular shaped and/or porous, un-doped silicon powder (hereinafter raw silicon powder) to spherical shaped, dense, and doped Si powder (hereinafter fine silicon powder) using atmospheric pressure inductively coupled thermal plasma. The system **1300** comprises a chamber **1302** configured to receive and process various gases and the raw silicon powder and comprises a receptacle **1304** arranged at the bottom of the chamber **1302** to collect the fine silicon powder produced by the chamber **1302**. The system **1300** further comprises a source supplying the raw silicon powder (hereinafter the powder source) **1306**, a plurality of gas sources **1308** supplying a plurality of gases, a power supply **1310**, and a controller **1312**. The controller **1312** controls supply of the raw silicon powder from the powder source **1306** to the chamber **1302**, supply of gases from the gas sources **1308** to the chamber **1302**, and power supplied by the power supply **1310** to the coils **1320**.

[0254] The chamber comprises an upper portion **1314** having a first cross-sectional area (e.g., a first diameter), a middle portion **1316** having a second cross-sectional area (e.g., a second diameter), and a bottom portion **1318** having a third cross-sectional area (e.g., a third diameter). The third cross-sectional area is less than the first cross-sectional area, and the first cross-sectional area is less than the second cross-sectional area. The upper portion **1314** comprises inlets for receiving the raw silicon powder and the various gases from the powder source **1306** and the gas sources **1308** as described below. A coil **1320** is arranged around the upper portion **1314**. The coil **1320** is connected to the power supply **1310**. The bottom portion **1318** is funnel shaped and is connected to the receptacle **1304**.

[0255] The upper portion **1314** comprises three concentric inlets formed by three concentric tubes: an inner tube **1326**, a middle tube **1324** coaxially surrounding the inner tube **1326**, and an outer tube **1322** defined by an outer wall of the middle tube **1324** and an inner wall of the upper portion **1314**. The tubes **1322**, **1324**, **1326** extend vertically downwards from a top end of the upper portion **1314** to approximately a midpoint of the upper portion **1314**. The coil **1320** is arranged around the upper portion **1314** between about the midpoint of the upper portion **1314** and a bottom end of the upper portion **1314**.

[0256] The raw silicon powder from the powder source **1306** is mixed with a carrier gas (e.g., H_2) supplied by one of the gas sources **1308**, and the mixture is supplied to the chamber **1302** through the inner tube **1326**. A dopant gas (e.g., B_2H_6 for p-type; and PH_3, AsH_3 for n-type) supplied by one of the gas sources **1308** is supplied to the chamber **1302** through the middle tube **1324**. A sheath gas (e.g., an inert gas such as Ar) supplied by one of the gas sources **1308** is supplied to the chamber **1302** through the outer tube **1322**. Power is supplied to the coil **1320** by the power supply **1310** to generate an inductively coupled thermal plasma (ICTP). A lower region of the upper portion **1314** surrounded by the coil **1320** is called a hot zone (identified at **1328**). The plasma heats and melts the raw silicon powder in the hot zone.

[0257] The dopant containing neutral molecules, radicals and ions adsorb and react with the surface of the molten Si particles so that dopant atoms diffuse into the molten Si particles, and H_2 gas desorbs from the surface. The small molten silicon particles become spherical in shape, and any internal voids in the particles bubble out to minimize surface energy. After the spherical molten Si particles fall from the plasma in the hot zone **1328**, the spherical molten Si particles solidify and cool down in the middle portion **1316** of the chamber **1302** (identified as a cooling zone **1330**) and are collected in the receptacle **1304**.

[0258] FIG. **10**G shows a temperature profile of the process performed in the chamber **1302**, where d is the distance measured from the top of the chamber **1302**. The final particle size distribution of the Si particles is controlled by the starting particle size distribution, which can be controlled by mesh sizes as described above. The dopant concentration can be controlled by controlling the percentage of the dopant in the carrier gas and a duration for which the Si particles are exposed to the high temperatures produced by the inductively coupled plasma. The duration is a function of the length of the coil **1320**, the flow rate of the carrier gas, and gravity.

[0259] The plasma is on (i.e., present) mainly in the lower region of the upper portion **1314** surrounded by the coil **1320** (i.e., the hot zone **1328**). The plasma is off (i.e., not present) in the cooling zone **1330** (i.e., the middle portion **1316**). In the hot zone **1328**, individual silicon particle falls into the plasma where it melts, spheroidizes, densifies, and mixes with dopant while falling through the plasma. In the cooling zone **1330**, since the plasma is off (i.e., not present), temperature drops, and the particle solidifies and cools down. The duration for doping a particle is the time for which the particle stays in the plasma, which approximately equals the length of the hot zone **1328** (i.e., the height of the lower region of the upper portion **1314** surrounded by the coil **1320**) and a speed at which the particle falls through the plasma. The speed is a function of the flow rate of the carrier gas, the temperature of the hot zone **1328**, and gravity.

[0260] The ICTP method is better than the PREP method in many respects. The porous and/or irregular shaped (i.e., the raw) silicon powder used in the ICTP method is typically mass produced without dopants and can be purchased at very low price comparing to solid silicon electrodes used in the PREP method. The ICTP method of converting the raw silicon powder into the fine spherical shaped powder described above is more cost effective than the PREP method, which converts silicon electrode to spherical shaped powder.

[0261] The particle size distribution (PSD) of a powder or granular material such as the powder manufactured using the PREP or ICTP method described above is a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to size. The most common method of determining PSD is sieve analysis where powder is separated on sieves of different sizes (e.g., as described with reference to FIG. **10**D above). Thus, the PSD is defined in terms of discrete size ranges: for example, "% of sample between 45 μm and 53 μm", when sieves of these sizes are used. The PSD is usually determined over a list of size ranges that covers nearly all the sizes present in the sample. Some methods of determination allow much narrower size ranges to be defined than can be obtained by using sieves, and are applicable to particle sizes outside the range available in sieves. However, the notion of a sieve that retains particles above a certain size and passes particles below that size is commonly used in presenting PSD data.

[0262] The PSD may be expressed as a range analysis in which the amount in each size range is listed in order. The PSD may also be presented in cumulative form in which the total of all sizes retained or passed by a single notional sieve is given for a range of sizes. Range analysis is suitable when a particular ideal mid-range particle size is being sought while cumulative analysis is used where the amount of under-size or over-size is to be controlled.

[0263] Before a PSD can be determined, a representative sample is obtained. In the case where the material to be analyzed is flowing, the sample is withdrawn from the stream in such a way that the sample has the same proportions of particle sizes as the stream. Preferably many samples of the whole stream are taken over a period instead of taking a portion of the stream for the whole time. After sampling, the sample volume typically needs to be reduced. The material to be analyzed is blended and the sample is withdrawn using techniques that avoid size segregation (e.g., using a rotary divider).

[0264] Various PSD measurement techniques may be used to measure the particle size of the silicon powder used in the systems and methods of the present disclosure. Some examples of the PSD measurement techniques are described below. For example, sieve analysis is a simple and inexpensive technique. Sieve analysis methods may include simple shaking of the sample in sieves until the amount retained becomes more or less constant. This technique is well-suited for bulk materials.

[0265] Alternatively, materials can be analyzed through photo-analysis procedures. Unlike sieve analyses which can be time-consuming and sometimes inaccurate, taking a photo of a sample of the materials to be measured and using software to analyze the photo can result in rapid, accurate measurements. Another advantage is that the material can be analyzed without being handled.

[0266] In other examples, PSDs can be measured microscopically by sizing against a graticule and counting. For a statistically valid analysis, millions of particles are measured. Automated analysis of electron micrographs is used to determine particle size within the range of 0.2 to 100 μm.

[0267] Coulter counter is an example of electro-resistance counting methods that can measure momentary changes in conductivity of a liquid passing through an orifice that take place when individual non-conducting particles pass through. The particle count is obtained by counting pulses. This pulse is proportional to the volume of the sensed particle. Very small sample aliquots can be examined using this method.

[0268] Other examples include sedimentation techniques. These techniques are based on study of terminal velocity acquired by particles suspended in a viscous liquid. These techniques determine particle size as a function of settling velocity. Sedimentation time is longest for the finest particles. Accordingly, this technique is useful for sizes below 10 μm. Sub-micrometer particles cannot be reliably measured due to the effects of Brownian motion. A typical measuring apparatus disperses the sample in liquid, then measures the density of the column at timed intervals. Other techniques determine the optical density of successive layers using visible light or x-rays.

[0269] Laser diffraction methods depend on analysis of the halo of diffracted light produced when a laser beam passes through a dispersion of particles in air or in a liquid. The angle of diffraction increases as particle size decreases. Accordingly, this method is particularly good for measuring sizes between 0.1 and 3,000 μm. Due to advances in data processing and automation, this is the dominant method used in industrial PSD determination. This technique is relatively fast and can be performed on very small samples. This technique can generate a continuous measurement for analyzing process streams. Laser diffraction measures particle size distributions by measuring the angular variation in intensity of light scattered as a laser beam passes through a dispersed particulate sample. Large particles scatter light at small angles relative to the laser beam and small particles scatter light at large angles. The angular scattering intensity data is then analyzed to calculate the size of the particles responsible for creating the scattering pattern using the Mie theory or Fraunhofer approximation of light scattering. The particle size is reported as a volume equivalent sphere diameter.

[0270] In laser obscuration time (LOT) or time of transition (TOT) method, a focused laser beam rotates at a constant frequency and interacts with particles within the sample medium. Each randomly scanned particle obscures the laser beam to a dedicated photo diode, which measures the time of obscuration. The time of obscuration t directly relates to the particle's diameter D by the equation D=V*t, where V is the beam rotation velocity.

[0271] In acoustic spectroscopy or ultrasound attenuation spectroscopy, ultrasound is used instead of light to collect information on the particles that are dispersed in fluid. The dispersed particles absorb and scatter ultrasound. Instead of measuring scattered energy versus angle, as with light, in the case of ultrasound, measuring the transmitted energy versus frequency is a better choice. The resulting ultrasound attenuation frequency spectra are the raw data for calculating particle size distribution. It can be measured for any fluid system with no dilution or other sample preparation. Calculation of particle size distribution is based on theoretical models that are well verified for up to 50% by volume of dispersed particles. As concentration increases and the particle sizes approach nanoscale, conventional modelling need to include shear-wave re-conversion effects to accurately reflect the real attenuation spectra.

[0272] After the silicon powder produced by the PREP or ICTP system shown in FIGS. **10**E and **10**F is sieved using the system shown in FIG. **10**D, the PSD of the silicon particles is determined using one or more of the PSD measurement techniques described above. The powder selected for use in the systems and methods of the present disclosure is denser and more spherical. For example, 90 wt. % of the powder has the particle size in the range of 40-100 μm (or, in another example, in the range of 50-90 μm), defined as volume-based particle size D=2*[3*V/(4*π)]^(1/3)). While the term sphere or spherical is used to describe the particles' shape, at least 90% particles have a volume-based particle size that is not more than 5% less than the measured longest diameter (measured using a microscope).

[0273] A silicon substrate can fracture and chip due to thermal impact during printing. The cracks can propagate in z direction, which may break the printed component **1201**. Therefore, a steel substrate **1208** is used to avoid the damage that can occur to the printed component when the silicon substrate is used to print the silicon component. The melting point of steel is higher than that of silicon and therefore does not melt during silicon printing. Steel is only one example for the substrate material; many other metals, alloys, and non-brittle materials can be used instead as the substrate **1208** so long as the melting point of the material used for the substrate is greater than the melting point of silicon (or of the nonmetallic material **1210** used to print the component **1201**).

[0274] An energy density of the electron beam is computed to define the intensity of the electron beam energy. Specifically, the energy density is equal to (Electron beam power x Exposure time)/(Point distance×Hatch distance). This equation gives the 2D energy density without considering the layer thickness of the powder and defines the intensity of the electron beam energy in the X-Y plane.

[0275] In the present disclosure, the layer thickness is set to such a value (e.g., 30 μm) that only 2D energy density is needed to calculate the intensity of the electron beam energy. Too low of an energy density can lead to a small size of a melted pool that is unable to melt all the powder particles in a layer. The un-melted silicon powder creates discontinuous melting pools during cooling, which increases the surface roughness and pores in the current layer. This occurs when the energy density is less than 5 $\mu J/\mu m^2$, for example.

[0276] As the energy density increases, the size of the melting pool increases, and the melted droplets have better flowability. The printed component has less pores, and the relative density of the printed component increases. This corresponds to energy density level between 5-14 $\mu J/\mu m^2$, for example. However, if the energy density is increased further, the silicon powder can be over-burnt, and the printed component can lose its geometry accuracy.

[0277] In the present disclosure, for printing silicon, the controller **1234** may set the energy density in a range between 10-14 $\mu J/\mu m^2$, for example. The silicon powder fully melts and the printed silicon components are fully dense when the energy density is set in this range.

[0278] A plurality of layers (e.g., about fifty layers) of silicon, called buffer layers **1228**, are initially printed on the steel substrate **1208**. Each layer of the buffer layers **1228** is printed once and is printed quickly (i.e., with fast electron beam scanning). For example, the electron beam power may be set to 200 W, and the exposure time may be set to 50 μs. In this example, the corresponding energy density is only 2.1 $\mu J/\mu m^2$. Due to the low energy density, some of the silicon powder may not fully melt. However, the purpose of the buffer layers **1228** is not to fully melt the silicon powder. Rather, as already explained above in detail, the buffer layers **1228** can avoid inconsistency of thermal expansion between the steel substrate **1208** and the lower layers of printed silicon component **1201** that are subsequently printed on top of the buffer layers **1228**.

[0279] After printing the buffer layers **1228**, the printing of the component **1201** begins. The component **1201** is printed on top of the buffer layers **1228** using double printing for each layer of the component **1201**. For example, the electron beam power in the first printing of a layer (also called printing a first sublayer) may be set to 240 W (higher than that used to printer the buffer layers **1228**), and the exposure time may be set to 50 μs (i.e., the first sublayer is also printed quickly; approximately similarly to the buffer layers **1228**).

[0280] The second printing of the layer (also called printing the second sublayer) repeats the path of the first printing. The electron beam power and exposure time are increased (e.g., to 350 W and 150 μs) during the second printing. Accordingly, the energy density for printing the second sublayer is greater than the energy density for printing the first sublayer. For example, using the above examples of electron beam power and exposure times, the energy densities for the printing of the two sublayers of each layer may be 2.5 $\mu J/\mu m^2$ and 11.0 $\mu J/\mu m^2$ respectively.

[0281] The first printing (i.e., the printing of the first sublayer) melts some of the silicon powder in this layer and also defines the geometry of the component **1201**. Then the second printing fully melts all of the silicon powder left un-melted in the first printing. The higher energy density in the second printing also elevates the temperature of the printed silicon component **1201** to a high level for slow cooling in the fast heating-cooling cycles in printing. The slow cooling of the currently printed layer serves a similar thermal purpose for subsequently printed layers as that served by the buffer layers **1228** for the currently printed layer.

[0282] The controller **1234** selects the energy density of the second printing such that the silicon powder fully melts and over-burning of the silicon powder is also avoided. This double printing method also protects the printed components from contamination due to spatter ejection of particles, thus avoiding pores induced by the spatter ejection, which is described below.

[0283] Spatter ejection occurs when bright (hot) particles of silicon (or the nonmetallic material **1210**) are ejected away from the melting pool due to recoil pressure during printing of each layer. These particles cool down in flight and may land on the printed component. The landed spatter ejection particles are generally bigger than the size of the silicon powder and might not be fully melted during printing of the next layer. This can cause porosity problem and reduce the strength of the printed component.

[0284] Spatter ejection can be caused by high energy density and/or low printing speed. According to the present disclosure, the double printing method of printing a layer prints the first sublayer of the layer with a low energy density electron beam to define the geometry in first printing. Using vacuum instead of an inert gas flow in the vacuum chamber **1202** during printing significantly reduces spatter. The low energy density (e.g., 2.5 $\mu J/\mu m^2$) and high printing speed (e.g., 1300 mm/s) further reduces the intensity of spatter ejection. Most of the silicon powder is melted in this step and solidified around the un-melted silicon powders after the electron beam **1226** stops. This prevents the un-melted powder from spattering by the recoil pressure. Then the second printing (i.e., the printing of the second sublayer on top of the first sublayer) with a high energy density electron beam and slower printing speed than the first printing fully melts all the un-melted silicon powder, and the intensity of spatter ejection is substantially reduced. The double printing strategy effectively reduces the intensity of spatter ejection, which significantly minimizes or eliminates porosity problem caused by spatter ejection.

[0285] FIG. **11**A shows a method **1300** for printing a component of a nonmetallic material on a metal substrate using buffer layers and double printing according to the present disclosure. FIG. **11**B shows the double printing method **1350** in further detail. For example, the methods **1335** and **1350** are performed by the controller **1234**.

[0286] In FIG. **11**A, at **1336**, the method **1335** filters or screens a stock of silicon powder manufactured using PREP by using one or more meshes and a vibration system (e.g., as shown in FIG. **10**D). At **1338**, the method **1335** prints a plurality of buffer layers of the nonmetallic material on the metal substrate prior to printing the component layers. At **1340**, the method **1335** prints each component layer on top of the buffer layers using the double printing method **1350** shown in detail in FIG. **11**B.

[0287] At **1342**, the method **1335** determines if all the layers of the component are printed. At **1344**, if all the layers of the component are not yet printed (i.e., if printing of the component is not yet completed), the method **1335** feeds the filtered or screened powder of the nonmetallic material to the powder bed to print the next layer of the component; and the method **1335** returns to **1340**. At **1346**, if all the layers of the component are printed (i.e., if printing of the component is completed), the method **1335** separates the printed component of the nonmetallic material from the metal substrate; and the method **1335** ends.

[0288] FIG. **11**B shows the double printing method **1350** in further detail. At **1352**, the method **1350** selects first and second angles for printing first and second sublayers of a layer of the component. At **1354**, the method **1352** prints, in a first pass, the first sublayer of the layer of the component using a fast scanning, low-power electron beam oriented at the selected first angle. At **1356**, the method **1352** prints, in a second pass, the second sublayer of the layer of the component using a slow scanning, high-power electron beam oriented at the selected second angle.

[0289] At **1358**, the method **1350** determines if all the layers of the component are printed. At **1360**, if all the layers of the component are not yet printed (i.e., if printing of the component is not yet completed), the method **1350** changes at least one of the first and second angles to be used for printing the next layer of the component; and the method **1350** returns to **1354**. The method **1350** ends if all the layers of the component are printed (i.e., if printing of the component is completed).

[0290] Thus, the advantages of the system **1200** and the method **1335** according to the first solution of the present disclosure include the following. The powder of the nonmetallic material manufactured using PREP or ICTP has much higher quality as compared to the powders traditionally manufactured with gas atomization. The particles of the powder manufactured using PREP or ICTP are also highly spherical and have smooth surfaces. Accordingly, the flowability and spreadability of the powder made using PREP or ICTP are much better than those of the powder made using gas atomization or chemical vapor deposition or crash of silicon solid. Further, the diameter of the particles is controlled and selected using one or more meshes and vibration as explained above.

[0291] The metal (e.g., steel) substrate protects the printed silicon component from fracturing. Ideally, silicon substrate is the only or preferred candidate as the substrate material. However, silicon substrate can fracture when subjected to high thermal load (or high temperature gradient) during printing, and the cracks can propagate through the printed silicon component causing fracturing. Steel being a ductile material can withstand the high temperature gradient and does not fracture.

[0292] The buffer layers reduce the CTE mismatch between the steel substrate and the printed silicon (i.e., between metal substrate and nonmetallic layers of the component being printed on the metal substrate). Further, the first printing (i.e., printing the first sublayer of each layer of the component) defines the component geometry. Most of silicon powder is melted in the first printing. The dissipation of melting pool restrains the un-melted silicon powder surrounded by the melted silicon. Therefore, spatter ejection is substantially reduced together with fast printing speed in the first printing. This avoids pores or voids in the printed component that can be induced by spatter ejection. Then the second printing fully melts all the un-melted silicon powder and elevates the component temperature to a high level before the printing of the next layer starts.

[0293] FIGS. **12**A-**12**C show a powder bed based system and method for 3D printing a component of a nonmetallic brittle material on a substrate of the same nonmetallic material according to the crack free printing method of the present disclosure. An electron beam generator is configured to supply an electron beam to print a layer of the nonmetallic material on the substrate while a heater continues to heat the substrate and a region of a chamber surrounding the substrate during the printing.

[0294] FIG. **12**A shows a powder bed based system **1400** for 3D printing a component **1401** of a nonmetallic material on a substrate of the same nonmetallic material. The system **1400** comprises a vacuum chamber **1402**. The vacuum chamber **1402** comprises a first plate **1404** and a second plate **1406**. The first plate **1404** supports a substrate **1408** on which the component **1401** is printed. Accordingly, the first plate **1404** is also called a building plate, a building platform, a printing plate, or another suitable name.

[0295] The second plate **1406** stores the nonmetallic material **1410**. A dose bar or a powder wiper **1412** supplies the nonmetallic material **1410** to the substrate **1408** prior to printing each layer. Accordingly, the second plate **1406** is also called a feeding plate, a dosing plate, or another suitable name.

[0296] The vacuum chamber **1402** comprises an observation window **1414**. The observation window **1414** is coated with a film to reduce heat dissipation. The system **1400** further comprises an electron beam generator **1420**, which generates an electron beam **1426** onto the substrate **1408** during printing. For example, the electron beam generator **1420** is similar to the electron beam generator **1170** shown in FIG. **9**B. Accordingly, the electron beam generator **1420** is not described in detail for brevity.

[0297] The vacuum chamber **1402** is thermally insulated with an insulating material **1428**. The insulating material **1428** is described below in further detail. A heater **1430** is used to heat the substrate **1408** before and during the printing of the component **1401**. A layer of the insulating material **1428** is arranged between the top of the first plate **1404** and the bottom of the heater **1430**. One or more heaters **1432** are used to heat the region surrounding the substrate **1408** during printing. A temperature sensor **1434** is used to sense the temperature of the region surrounding the substrate **1408**. The heaters **1430**, **1432** are controlled based on the sensed temperature.

[0298] FIG. **12**B shows additional elements of the system **1400**. The system **1400** further comprises a vacuum pump **1418** that is connected to the vacuum chamber **1402** via a valve **1416** to maintain a high vacuum in the vacuum chamber **1402**. For example, the pressure in the vacuum chamber **1402** can be <1E-5 Torr, which is the same as <0.01 mTorr or <1.33 mPa. The system **1400** further comprises a plate movement assembly **1452** to move the first plate **1404** downwards and to move the second plate **1406** upwards during printing. The system **1400** further comprises a power supply and a temperature controller (shown as temperature/heater power controller **1456**) to maintain the desired temperatures inside the hot zone. The system **1400** further comprises a controller **1454** that controls all the elements of the system **1400** as explained below.

[0299] Current 3D printing equipment is designed for printing metals which are ductile materials and are more tolerant to thermal stress. Therefore, ex-situ annealing can be used to reduce thermal stress. However, the current conventional 3D printing equipment is not capable of uniform heating and maintaining substrate temperatures greater than about 600° C. Accordingly, large temperature gradients can occur in the silicon component being printed in these machines since the melt pool temperature is greater than the melting point of silicon (1414° C.), and adjacent silicon (i.e., silicon adjacent to the melt pool) is likely at temperatures <700 C. In addition, in the current 3D printing equipment, the cool down is fast and not controlled. The large temperature gradient during printing and fast cooling down lead to micro-cracks in the 3D-printed silicon components using conventional 3D printers. The micro-cracks cannot be healed in ex-situ annealing.

[0300] Therefore, the system **1400** provides the 3D printing equipment with a low temperature gradient. The system **1400** uses one or multiple heaters **1430**, **1432** along with thermal insulation (i.e., the insulating material **1428**) to minimize the temperature gradient during printing, in-situ annealing, and cooling. The heaters **1430**, **1432** can be either resistive or inductive heaters, infrared (IR) lamp radiation heaters, or blue light heaters (e.g., using blue LEDs). The insulating material **1428** can be either rigid carbon fiber insulation or soft graphite felt or combination of both. Due to high reactivity of carbon and melted silicon with oxygen at elevated temperatures during printing, the system **1400** needs to be vacuum tight.

[0301] In one embodiment, vacuum chamber **1402** is rectangular in shape with rigid insulation plates (i.e., rigid plates of the insulating material **1428**) covering the inside at top and bottom, left and right, front and back. In another embodiment, the vacuum chamber **1402** is cylindrical in shape with rigid insulation plates covering the inside at top and bottom and rigid insulation cylinder shielding the surrounding cylindrical wall. Other shapes are contemplated.

[0302] The insulation plate or cylinder can be made of multiple layers, such as rigid insulation/rigid insulation, graphite/rigid insulation, rigid insulation/felt, graphite/felt, carbon fiber composite (CFC)/felt. Felt is essentially a cloth-like soft material made of many layers of carbon fiber. Insulation prevents heat from escaping and helps in maintaining the high temperature uniformly throughout the printing process (i.e., insulation and heaters help in maintaining a low thermal gradient throughout the printing process).

[0303] For 3D printing of silicon, graphite resistive heaters are preferred. A graphite susceptor (i.e., a shield, not shown) can be placed inside the side heater **1432** to protect the heater **1432**. The silicon powder is selected as described in the fully dense printing method, and the selection process is therefore not repeated for brevity. The silicon powder is dosed by the powder wiper **1412** after completion of printing of each layer. When the printing of all layers is completed, the printed component **1401** is embedded in silicon powder. The silicon powder can also prevent heat from dissipating in the horizontal direction. The silicon powder has low thermal conductivity and slightly slows cooling of the printed component.

[0304] Due to the brittle nature of silicon, the substrate temperature for 3D printing is preferred to be greater than the ductile to brittle transition temperature or DBTT of silicon (i.e., greater than 1000° C.) during printing and annealing of the printed component **1401** to prevent thermal stress buildup. For example, the annealing temperatures are preferred to be between 1100-1200° C. It is also preferred to cool down the printed component **1401** slowly at a controlled rate. For example, the cool down is preferred to be at a rate of less than 5° C./min from the annealing temperature to about 400° C., and is followed by backfill of an inert gas (e.g., Ar). The substrate **1408** for 3D printing of the component **1401** of silicon is preferably made of silicon to avoid

CTE mismatch between the substrate **1408** and the component **1401** and contamination from substrates made of other materials. The concept can be applied to other brittle materials such as alumina, silicon carbide, ceramics, etc.

[0305] FIG. **12**C shows a powder bed based method **1480** for 3D printing a component (e.g., element **1401**) of a nonmetallic material on a substrate (e.g., element **1408**) of the same nonmetallic material according to the second solution of the present disclosure. For example, the method **1480** is performed by the controller **1454**.

[0306] At **1482**, the method **1480** creates vacuum in a thermally insulated chamber. At **1484**, before starting the printing of the component **1401**, the method **1480** heats the substrate **1408** and a region proximate to the printing area (i.e., surrounding the substrate **1408**) using one or more heaters (e.g., heaters **1430**, **1432**).

[0307] At **1486**, the method **1480** feeds filtered or screened silicon powder to form a powder bed on the substrate **1408**. The method **1480** supplies an electron beam **1426** to print a layer of the silicon powder while maintaining the heat provided by the one or more heaters **1430**, **1432**. The method **1480** senses the temperature in the vacuum chamber **1402** (e.g., of the region surrounding the substrate) and maintains the temperature of the substrate **1408** and the surrounding region to a temperature greater than the DBTT of the silicon (or the nonmetallic material being used to print the component).

[0308] At **1488**, the method **1480** determines if all the layers of the component **1401** are printed (i.e., if the printing of the component is completed). The method **1480** returns to **1486** if all the layers of the component **1401** are not yet printed (i.e., if the printing of the component is not yet completed).

[0309] At **1490**, the method **1480** anneals the printed component **1401** while maintaining the heat supplied by the heaters **1430**, **1432** under the control of the controller **1454**. At **1492**, under the control of the controller **1454**, the method **1480** controls the annealing and the cooling of the printed component **1401** using the heaters **1430**, **1432**, the insulation **1428**, and using the silicon powder surrounding the printed component, and the method **1480** ends.

[0310] Thus, the system **1400** and method **1480** according to the crack free printing method includes adding heaters and thermal insulation to the metal 3D-printing equipment, which enables maintaining a lower temperature gradient during printing and in-situ annealing as well as slower cool down at a controlled cooling rate, which significantly reduces thermal stress in the printed silicon component and eliminates micro-cracks.

[0311] The conventional metal 3D printing equipment is not capable of maintaining temperatures above 600° C. and controlled cool down, which induces high thermal stress and causes micro-cracks in the printed silicon component and renders it useless. The solution also uses vacuum tight chamber to prevent oxidation of melted silicon, graphite based heaters, and carbon fiber based thermal insulations. The conventional metal 3D printing equipment does not require vacuum tight.

[0312] FIGS. **13**A-**15**B show systems and methods for bonding and repairing silicon components used in processing chambers and semiconductor processing tools. Throughout the following description, silicon components are used for example only. The following teachings can be used with components made from any nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

[0313] For example, a component such as a C-shaped shroud used in a processing chamber may be typically manufactured as a monolithic component. However, monolithic components are difficult to manufacture. Instead, it can be easier to manufacture a plurality of subcomponents of a component and then bond them to form a single component as described below.

[0314] Additionally, silicon components used in substrate processing systems may get chipped during manufacturing process or their use in processing chambers. It is expensive to discard and replace a component due to minor chipping. Instead, the chipped component can be repaired as described below so that the repaired component can be used instead of discarding and replacing the chipped component. The repair can lengthen the useful life of the component or reduce the scrap rate of manufacturing the component.

[0315] FIGS. **13**A-**13**C show a system and a method for bonding silicon components. FIGS. **14**A-**14**C show a system and a method for repairing silicon components. FIGS. **15**A and **15**B show a combined system for bonding and repairing silicon components in a single chamber. Again, silicon components are used for example only, and the systems and methods can be used with components made of any nonmetallic material such as silicon, silicon carbide, alumina, and ceramics.

[0316] FIG. **13**A shows a vacuum chamber **1502** of a system **1500** for bonding silicon components. The complete system **1500** is shown in detail in FIG. **13**B. In FIG. **13**A, the vacuum chamber **1502** of the system **1500** is shown in detail. The walls of the vacuum chamber **1502** are made of stainless steel. While not shown, the walls of the vacuum chamber **1502** are cooled by circulating a coolant such as water through the walls.

[0317] The vacuum chamber **1502** encloses a pedestal **1504**. The pedestal **1504** supports a susceptor **1506**. The pedestal **1504** and the susceptor **1506** can be rotated around Z axis. A heater **1508** is arranged around the pedestal **1504**. The heater **1508** can be arranged under the susceptor **1506** as shown. Alternatively, while not shown, the heater **1508** can be arranged on the sides of (i.e., around) the susceptor **1506** and the pedestal **1504**. The pedestal **1504**, the susceptor **1506**, and the heater **1508** are made of graphite.

[0318] A thermal insulation **1510** is disposed in the vacuum chamber **1502** around the pedestal **1504**, the susceptor **1506**, and the heater **1508**. The thermal insulation **1510** is made of rigid carbon fiber. Alternatively, the thermal insulation **1510** can include graphite wrapped with felt. The thermal insulation **1510** forms an insulated hot zone in the vacuum chamber **1502** around the pedestal **1504**, the susceptor **1506**, and the heater **1508**.

[0319] An electron gun **1520** is mounted to a sidewall of the vacuum chamber **1502** using a fixture **1522**. The electron gun **1520** is movable along Z axis. A component **1516** comprising a plurality of elements (i.e., subcomponents or pieces) is arranged on the susceptor **1506**. For example only, the component **1516** may include three elements **1516-1**, **1516-2**, and **1516-3**. The thermal insulation **1510** includes a slot **1512** through which an electron beam **1514** from the electron gun **1520** can irradiate the elements of the component **1516**. By moving the electron gun **1520** and rotating the pedestal **1504**, different portions of the elements of the component **1516** can be irradiated. In some examples, the pedestal **1504** may also be movable vertically along Z axis.

[0320] The electron beam **1514** bonds the elements **1516-1**, **1516-2**, and **1516-3** to form the component **1516** using a method described below with reference to FIG. **13**C. For example, the electron beam **1514** bonds the element **1516-1** to the element **1516-2** at **1517**, and the electron beam **1514** bonds the element **1516-2** to the element **1516-3** at **1518** using the method described below with reference to FIG. **13**C. Before describing the method, the remainder of the system **1500** is described below with reference to FIG. **13**B.

[0321] In FIG. **13**B, the system **1500** comprises a vacuum pump **1550** that is connected to the vacuum chamber **1502** via a valve **1552** to maintain a high vacuum in the vacuum chamber **1502**. For example, the pressure in the vacuum chamber **1502** can be <1E-5 Torr, which is the same as <0.01 mTorr or <1.33 mPa. The system **1500** further comprises a pedestal movement assembly **1554** to rotate the pedestal **1504**. The system **1500** further comprises an electron gun e-beam generation and movement assembly **1555** to move the electron gun **1520**.

[0322] The system **1500** further comprises a power supply and a temperature controller (collectively shown as temperature/heater power controller **1556**) to maintain desired temperatures inside the hot zone (described below with reference to FIG. **13**C). The system **1500** further comprises an inert gas supply **1558** to supply an inert gas such as argon (Ar) to backfill the vacuum chamber **1502**. The system **1500** further comprises a controller **1560** that controls all the elements of the system **1500** as explained below with reference to FIG. **13**C.

[0323] FIG. **13**C shows a method **1600** for bonding silicon components. For example, the controller **1560** performs the method **1600** by controlling the various elements of the system **1500** as follows. At **1602**, the method **1600** includes cleaning the mating surfaces of the elements that are to be bonded to form a component (e.g., cleaning the mating surfaces of the elements **1516-1**, **1516-2**, and **1516-3** at **1517** and **1518** to form the component **1516**). At **1604**, the method **1600** includes arranging the elements of the component in a 3D electron beam printer or welder (e.g., on the susceptor **1506** in the vacuum chamber **1502**). No silicon powder is added between the mating surfaces of the elements to be bonded together (e.g., no silicon powder is added at **1517** and **1518**).

[0324] At **1606**, the method **1600** includes operating the pump **1550** to create vacuum in the vacuum chamber **1502** as described above with reference to FIGS. **13**A and **13**B. Additionally, the method **1600** includes operating the heater **1508** using the temperature/heater power controller **1556** to heat the elements of the component to above brittle to ductile transition point of silicon (>800° C.) in the insulated hot zone, which is created in the vacuum chamber **1502** using the thermal insulation **1510** as described above with reference to FIGS. **13**A and **13**B.

[0325] At **1608**, the method **1600** includes focusing the electron beam **1514** of the electron gun **1520** to a first area of a joint (e.g., **1517**) between two elements (e.g., **1516-1** and **1516-2**) until the silicon at the first area (i.e., silicon at portions of extremities of the two elements) melts and solidifies. The method **1600** may include slowly reducing the power of the electron beam **1514** to let the melt pool solidify at the last portion of a joint.

[0326] At **1610**, the method **1600** includes determining if all the areas of the joint (i.e., the entirety of **1517**) are melted and solidified. If all the areas of the joint are not melted and solidified, the method **1600** proceeds to **1612**. At **1612**, the method **1600** includes slowly rotating the component (by rotating the pedestal **1502** using the pedestal movement assembly **1554**) to select a next area of the selected joint for melting and solidification, after which the method **1600** returns to **1608**. The method **1600** can also include moving the electron gun **1520** using the electron gun movement assembly **1555** to irradiate different areas of a joint. If all the areas of the joint are melted and solidified, the method **1600** proceeds to **1614**.

[0327] At **1614**, the method **1600** includes determining if all the joints (e.g., **1517** and **1518**) of the component are melted and solidified (i.e., if all the elements of the component are joined or welded together to form the component). If all the joints of the component are not melted and solidified, the method **1600** proceeds to **1616**. At **1616**, the method **1600** includes selecting the next joint (e.g., **1518**) to be melted and solidified, after which the method **1600** returns to **1608**. For example, the method **1600** includes selecting the next joint by rotating the pedestal **1504** using the pedestal movement assembly **1554**. If all the joints are melted and solidified, the bonding of the elements to form the component (hereinafter the bonded component) is complete, and the method **1600** proceeds to **1618**.

[0328] At **1618**, the method **1600** includes annealing the joints of the bonded component. For example, the method **1600** includes controlling the heater **1508** using the temperature/heater power controller **1556** to heat the bonded component and hold the temperature at above 1000° C. for about an hour. Then the method **1600** includes slowly cooling the bonded component to about 700° C. at a rate of about <2 C/min, which is followed by a faster cooling of the bonded component to about 400° C. by powering off the heater **1508**.

[0329] At **1620**, the method **1600** includes backfilling the vacuum chamber **1502** with an inert gas such as argon (Ar) supplied by the inert gas supply **1558**. The method **1600** then includes opening of the vacuum chamber **1502** and unloading of the bonded component from the vacuum chamber **1502**. At **1622**, the method **1600** includes grinding off any excess silicon from the bonded component and re-cleaning the bonded component for use in a processing chamber or a substrate processing system such as that shown in FIG. **9**A.

[0330] FIG. **14**A shows a vacuum chamber **1702** of a system **1700** for repairing silicon components. The complete system **1700** is shown in detail in FIG. **14**B. In FIG. **14**A, the vacuum chamber **1702** of the system **1700** is shown in detail. The walls of the vacuum chamber **1702** are made of stainless steel. While not shown, the walls of the vacuum chamber **1702** are cooled by circulating a coolant such as water through the walls.

[0331] The vacuum chamber **1702** encloses a rotary table **1704**. A component **1716** to be repaired is arranged on the rotary table **1704**. For example, the component **1716** may include a chipped region **1717** that needs to be repaired. The rotary table **1704** is rotatable around Z axis. The rotary table **1704** is mounted to an arm **1706** using a fixture **1707**. The arm **1706** is rotatable around X axis. Thus, the rotary table **1704** is rotatable around Z and X axes. In some examples, the arm **1706** together with the rotary table **1704** may also be movable along X axis. The rotary table **1704** and the arm

1706 are made of graphite. A distal end of the arm **1706** may be extended and supported by a supporting structure (not shown) if the component **1716** and/or the rotary table **1704** are relatively heavy.

[0332] A heater **1708** is arranged under the rotary table **1704** and the arm **1706**. Alternatively, while not shown, the heater **1708** can be arranged along the sidewalls of the vacuum chamber **1702** around the rotary table **1704** and the arm **1706**. A thermal insulation **1710** is disposed in the vacuum chamber **1702** around the rotary table **1704**, the arm **1706**, and the heater **1708**. The thermal insulation **1710** is made of rigid carbon fiber. Alternatively, the thermal insulation **1710** can include graphite wrapped with felt. The thermal insulation **1710** forms an insulated hot zone in the vacuum chamber **1702** around the rotary table **1704**, the arm **1706**, and the heater **1708**.

[0333] An electron gun **1720** is mounted to a top wall of the vacuum chamber **1702** using a fixture **1722**. The electron gun **1720** is movable along X and Y axes. The thermal insulation **1710** includes a slot **1712** through which an electron beam **1714** from the electron gun **1720** can irradiate the chipped region **1717** of the component **1716**. By moving the electron gun **1720** and rotating the rotary table **1704** and the arm **1706**, different portions of the component **1716** can be irradiated.

[0334] Specifically, the rotary table **1704** can not only rotate around its own axis (Z axis) perpendicular to its plane but can also be rotated around the axis parallel to its plane (X axis) by rotating the arm **1706**. These two rotations allow moving the chipped region **1717** to the top so as to face the electron gun **1720**. By moving the electron gun **1720** along X and Y axes, the electron beam **1714** can be directed to the chipped region **1717**. To repair, the chipped region **1717** is filled with silicon powder, which the electron beam **1714** melts using a method described below with reference to FIG. **14**C. Before describing the method, the remainder of the system **1500** is described below with reference to FIG. **14**B.

[0335] In FIG. **14**B, the system **1700** comprises a vacuum pump **1750** that is connected to the vacuum chamber **1702** via a valve **1752** to maintain a high vacuum in the vacuum chamber **1702**. For example, the pressure in the vacuum chamber **1702** can be <1E-5 Torr, which is the same as <0.01 mTorr or <1.33 mPa. The system **1700** further comprises movement assemblies to rotate the rotary table **1704** and the arm **1706**, which are collectively shown as arm and rotary table movement assemblies **1754**. The system **1700** further comprises an electron gun e-beam generation and movement assembly **1755** to move the electron gun **1720**.

[0336] The system **1700** further comprises a power supply and a temperature controller (collectively shown as temperature/heater power controller **1756**) to maintain desired temperatures inside the hot zone (described below with reference to FIG. **14**C). The system **1700** further comprises an inert gas supply **1758** to supply an inert gas such as argon (Ar) to backfill the vacuum chamber **1702**. The system **1700** further comprises a controller **1760** that controls all the elements of the system **1700** as explained below with reference to FIG. **14**C.

[0337] FIG. **14**C shows a method **1800** for repairing silicon components. For example, the controller **1760** performs the method **1800** by controlling the various elements of the system **1700** as follows. At **1802**, the method **1800** includes arranging a chipped component (e.g., the component **1715** with the chipped region **1717**) in an EBM chamber (e.g., the vacuum chamber **1702**). The method **1800** includes rotating the rotary table **1704** and the arm **1706** using the arm and rotary table movement assemblies **1754** so that the chipped region **1717** is facing up towards the electron gun **1720**.

[0338] At **1804**, the method **1800** includes filling the chipped region **1717** with silicon powder (e.g., including particles having a diameter in the range 100 um-3 mm and the same resistivity as the component **1715**). At **1806**, the method **1800** includes operating the pump **1750** to create vacuum in the vacuum chamber **1702** as described above with reference to FIGS. **14**A and **14**B. Additionally, the method **1800** includes operating the heater **1708** using the temperature/heater power controller **1756** to heat the component to above brittle to ductile transition point of silicon (>800° C.) in the insulated hot zone, which is created in the vacuum chamber **1702** using the thermal insulation **1710** as described above with reference to FIGS. **14**A and **14**B.

[0339] At **1808**, the method **1800** includes focusing the electron beam **1714** of the electron gun **1720** on the silicon powder in the chipped region **1717** of the component to completely melt the silicon powder and a portion of the chipped region **1717**. The method **1800** may also include moving the electron gun **1720** using the electron gun movement assembly **1755**. At **1810**, the method **1800** includes slowly reducing the electron beam power to let the melt pool in the chipped region **1717** solidify.

[0340] At **1812**, the method **1800** includes annealing the repaired component. For example, the method **1800** includes controlling the heater **1708** using the temperature/heater power controller **1756** to heat the repaired component and hold the temperature at above 1000° C. for about an hour. Then the method **1800** includes slowly cooling the repaired component to about 700° C. at a rate of about ≤2 C/min, which is followed by a faster cooling of the repaired component to about 400° C. by turning off the heater **1708**.

[0341] At **1814**, the method **1800** includes backfilling the vacuum chamber **1702** with an inert gas such as argon (Ar) supplied by the inert gas supply **1758**. The method **1800** then includes opening of the vacuum chamber **1702** and unloading of the repaired component from the vacuum chamber **1702**. At **1816**, the method **1800** includes grinding off any excess silicon from the repaired region and re-cleaning the repaired component for use in a processing chamber or a substrate processing system such as that shown in FIG. **9**A.

[0342] FIG. **15**A shows a system **1900** for bonding and repairing silicon components in a single vacuum chamber **1902**. Essentially, the system **1900** is a combination of the systems **1500** and **1700** since both bonding and repairs can be performed in a single vacuum chamber **1902**. The vacuum chamber **1902** includes all of the elements of the vacuum chamber **1702** and further includes the following elements of the vacuum chamber **1502**: the slot **1512** is added to the thermal insulation **1710**, and the electron gun **1520** is mounted to the sidewall of the vacuum chamber **1902** using the fixture **1522**.

[0343] Otherwise, the vacuum chamber **1902** is identical to the vacuum chamber **1702** and is therefore not described again for brevity.

[0344] In the vacuum chamber **1902**, the elements **1516-1**, **1516-2**, **1516-3** of the component **1516** can be arranged on the rotary table **1704** and can be bonded using the electron gun **1520** as described above with reference to FIGS. **13**A-**13**C. Further, the chipped region **1717** on the component **1716** can be repaired using the electron gun **1720** as described above with reference to FIGS. **14A-14**C.

[0345] FIG. **15**B shows additional elements of the system **1900**. The system **1900** includes all of the elements of the system **1700** shown in FIG. **14**B and further includes the electron gun movement assembly **1555** of the system **1500**. A controller **1954** includes the functionalities of the controllers **1554** and **1754**. The controller **1954** can perform the methods **1600** and **1800** described above, which are not described again for brevity.

[0346] In some examples, the system **1700** can also be used (repurposed) to bond pieces of a component as described with reference to FIGS. **13A-13**C. In other examples, two robot arms can be provided in the system **1400**, which can then be used to bond as well as repair component. For example, in a bonding application, the two robot arms can be used to hold two pieces of a component. The two robot arms can be moved with appropriate degrees of freedom such that the electron gun can bond the two pieces to form the component. In a repair application, one or both robot arms can be used to hold the component to be repaired. Then one or both robot arms can be with appropriate degrees of freedom such that the electron gun can melt the powder in the defective region of component to repair the component. In still other examples, in the system **1900**, both electron guns can be used to bond elements of a component, and both electron guns can be used to repair multiple chips on a defective component. Many other variations and uses of the various systems and methods described herein are contemplated.

[0347] FIGS. **16A-16**C show bonding of two silicon components using the systems and methods of FIGS. **13A-13**C, **15**A, and **15**B resulting in a grain boundary between the two components due mismatched crystalline orientation. For example, a silicon component **2000** is formed by bonding two silicon subcomponents **2002** and **2004** respectively shown as Subcomponent **1** and Subcomponent **2**. FIG. **16**A shows the subcomponents **2002**, **2004** before bonding. FIG. **16**B shows the subcomponents **2002**, **2004** during bonding. FIG. **16**C shows the silicon component **2000** after the bonding of the subcomponents **2002**, **2004**.

[0348] In FIG. **16**A, each of the first and second subcomponents **2002**, **2004** has a single crystalline structure. The first and second subcomponents **2002**, **2004** respectively have edges **2006**, **2008** at which the two subcomponents **2002**, **2004** are to be bonded.

[0349] The edges **2006**, **2008** are also called welding surfaces. In a single-crystal or monocrystalline material such as the first and second subcomponents **2002** and **2004**, a crystal lattice of the entire individual subcomponent is continuous and unbroken to the edges with no grain boundaries. A grain boundary is an interface between two grains or crystallites in a polycrystalline material. The edges **2006**, **2008** of the two subcomponents **2002** and **2004** comprise crystals with two different crystalline orientations. When bonding the two subcomponents **2002** and **2004**, it is impossible to exactly align their crystalline orientations in atomic scale. The two subcomponents **2002** and **2004** are bonded at the edges **2006**, **2008** by applying the electron beam **1514** at the edges **2006**, **2008** as described with reference to FIGS. **13**A-**13**C, **15**A, and **15**B.

[0350] In FIG. **16**B, a molten zone **2010** is formed at the edges **2006**, **2008** of the subcomponents **2002** and **2004** when the electron beam **1514** irradiates at the edges **2006**, **2008**. The molten zone **2010** is allowed to solidify, annealed, and allowed to cool as described with reference to FIGS. **13**A-**13**C, **15**A, and **15**B.

[0351] In FIG. **16**C, the bonded the subcomponents **2002** and **2004** form the component **2000**. A gain boundary **2012** is formed at the bond (i.e., in the bonded region or the joint) between the subcomponents **2002** and **2004** due to their inevitable crystalline orientation mismatch. The grain boundary **2012** is the seam of solidification of the melted material from the subcomponents **2002** and **2004** at the joint between the subcomponents **2002** and **2004**. The grain boundary **2012** can also be called the seam of the solidification from the subcomponents **2002** and **2004**.

[0352] The grain boundary **2012** is also formed if the subcomponents **2002** and **2004** are made of multi-crystalline silicon since each grain in the multi-crystalline silicon is a small single crystal. At the joint between the subcomponents **2002** and **2004** made of multi-crystalline silicon, a plurality of the grain boundary **2012** will be formed between each pair of two grains facing each other during solidification. The grain boundary **2012** will also be formed if a laser beam is used to melt the edges **2006**, **2008** to join the subcomponents **2002**, **2004** to form the component **2000**. The plurality of grain boundaries **2012** will also be formed if the joint between the edges **2006**, **2008** is filled with silicon powder and melted by the electron beam or the laser beam to form the component **2000**.

[0353] The grain boundary **2012** is a detectable feature of the bonded component **2000**. For example, if the component **2000** were monolithic (i.e., manufactured as a single piece and not manufactured by bonding two subcomponents), the component **2000** will not include the grain boundary **2012**. Further, if the subcomponents **2002** and **2004** are joined to form the component **2000** using a process other than the processes described with reference to FIGS. **13**A-**13**C, **15**A, and **15**B, the component **2000** will not include the grain boundary **2012** at the joint between the subcomponents **2002** and **2004**.

[0354] The foregoing description is merely illustrative in nature and is not intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure.

[0355] Further, although each of the embodiments is described above as having certain features, any one or more of those features described with respect to any embodiment of the disclosure can be implemented in and/or combined with features of any of the other embodiments, even if that combination is not explicitly described. In other words, the described embodiments are not mutually exclusive, and permutations of one or more embodiments with one another remain within the scope of this disclosure.

[0356] Spatial and functional relationships between elements (for example, between modules, circuit elements, semiconductor layers, etc.) are described using various terms, including "connected," "engaged," "coupled," "adjacent," "next to," "on top of," "above," "below," and "disposed." Unless explicitly described as being "direct," when a relationship between first and second elements is described in the above disclosure, that relationship can be a direct relationship where no other intervening elements are present between the first and second elements, but can also be an indirect relationship where one or more intervening elements are present (either spatially or functionally) between the first and second elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A OR B OR C), using a non-exclusive logical OR, and should not be construed to mean "at least one of A, at least one of B, and at least one of C."

[0357] In some implementations, a controller is part of a system, which may be part of the above-described examples. Such systems can comprise semiconductor processing equipment, including a processing tool or tools, chamber or chambers, a platform or platforms for processing, and/or specific processing components (a wafer pedestal, a gas flow system, etc.). These systems may be integrated with electronics for controlling their operation before, during, and after processing of a semiconductor wafer or substrate.

[0358] The electronics may be referred to as the "controller," which may control various components or subparts of the system or systems. The controller, depending on the processing requirements and/or the type of system, may be programmed to control any of the processes disclosed herein, including the delivery of processing gases, temperature settings (e.g., heating and/or cooling), pressure settings, vacuum settings, power settings, radio frequency (RF) generator settings, RF matching circuit settings, frequency settings, flow rate settings, fluid delivery settings, positional and operation settings, wafer transfers into and out of a tool and other transfer tools and/or load locks connected to or interfaced with a specific system.

[0359] Broadly speaking, the controller may be defined as electronics having various integrated circuits, logic, memory, and/or software that receive instructions, issue instructions, control operation, enable cleaning operations, enable endpoint measurements, and the like. The integrated circuits may include chips in the form of firmware that store program instructions, digital signal processors (DSPs), chips defined as application specific integrated circuits (ASICs), and/or one or more microprocessors, or microcontrollers that execute program instructions (e.g., software).

[0360] The program instructions may be instructions communicated to the controller in the form of various individual settings (or program files), defining operational parameters for carrying out a particular process on or for a semiconductor wafer or to a system. The operational parameters may, in some embodiments, be part of a recipe defined by process engineers to accomplish one or more processing steps during the fabrication of one or more layers, materials, metals, oxides, silicon, silicon dioxide, surfaces, circuits, and/or dies of a wafer.

[0361] The controller, in some implementations, may be a part of or coupled to a computer that is integrated with the system, coupled to the system, otherwise networked to the system, or a combination thereof. For example, the controller may be in the "cloud" or all or a part of a fab host computer system, which can allow for remote access of the wafer processing. The computer may enable remote access to the system to monitor current progress of fabrication operations, examine a history of past fabrication operations, examine trends or performance metrics from a plurality of fabrication operations, to change parameters of current processing, to set processing steps to follow a current processing, or to start a new process.

[0362] In some examples, a remote computer (e.g. a server) can provide process recipes to a system over a network, which may include a local network or the Internet. The remote computer may include a user interface that enables entry or programming of parameters and/or settings, which are then communicated to the system from the remote computer. In some examples, the controller receives instructions in the form of data, which specify parameters for each of the processing steps to be performed during one or more operations. It should be understood that the parameters may be specific to the type of process to be performed and the type of tool that the controller is configured to interface with or control.

[0363] Thus as described above, the controller may be distributed, such as by comprising one or more discrete controllers that are networked together and working towards a common purpose, such as the processes and controls described herein. An example of a distributed controller for such purposes would be one or more integrated circuits on a chamber in communication with one or more integrated circuits located remotely (such as at the platform level or as part of a remote computer) that combine to control a process on the chamber.

[0364] Without limitation, example systems may include a plasma etch chamber or module, a deposition chamber or module, a spin-rinse chamber or module, a metal plating chamber or module, a clean chamber or module, a bevel edge etch chamber or module, a physical vapor deposition (PVD) chamber or module, a chemical vapor deposition (CVD) chamber or module, an atomic layer deposition (ALD) chamber or module, an atomic layer etch (ALE) chamber or module, an ion implantation chamber or module, a track chamber or module, and any other semiconductor processing systems that may be associated or used in the fabrication and/or manufacturing of semiconductor wafers.

[0365] As noted above, depending on the process step or steps to be performed by the tool, the controller might communicate with one or more of other tool circuits or modules, other tool components, cluster tools, other tool interfaces, adjacent tools, neighboring tools, tools located throughout a factory, a main computer, another controller, or tools used in material transport that bring containers of wafers to and from tool locations and/or load ports in a semiconductor manufacturing factory.

1. A method of performing three-dimensional (3D) printing of a silicon component, the method comprising:
  adding powdered silicon to a 3D printing tool;
  for each layer of the 3D printing in a layer-by-layer process:
    forming a powder bed of the powdered silicon in the 3D printing tool;
    baking the powdered silicon in a temperature range of 650° C. to 750° C. under a high-vacuum condition in a range of 10-5 Torr to 10-7 Torr to decompose and remove surface oxides from the powdered silicon;
    forming a layer of the powder bed to a pre-determined thickness;
    directing a high-powered beam under the high-vacuum condition in a pre-determined pattern into the formed powder-bed, the high-powered beam having sufficient energy to melt the powdered silicon; and

making a determination as to whether additional layers in the 3D printing are needed; and

based on a determination that no additional layers are needed, cooling the silicon component at a pre-determined temperature ramp-down rate to ambient temperature of an environment in which the 3D printing tool is located.

2. The method of claim **1**, wherein the high-powered beam comprises an electron beam.

3. The method of claim **1**, wherein the method is performed within an inert gas environment.

4. The method of claim **3**, wherein the inert gas environment comprises at least one gas selected from gases including argon (Ar) and helium (He).

5. The method of claim **1**, wherein silicon particles in the silicon powder have a median size in a range of 45 μm to 55 μm and a distribution range of sizes between 10 μm to 100 μm.

6. The method of claim **1**, wherein a purity of the powdered silicon is generally greater than 99.99%.

7. The method of claim **1**, wherein a purity of the powdered silicon is generally greater than 99.9999%.

8. The method of claim **1**, wherein the powdered silicon is baked in a temperature range of 700° C. under a high-vacuum condition in a range of 10-6 Torr to decompose and remove surface oxides from the powdered silicon.

9. The method of claim **1**, wherein the powdered silicon comprises substantially spherical particles.

10. The method of claim **1**, wherein the powdered silicon is formed by a fluidized-bed chemical vapor deposition (FB-CVD) system using silane (SiH_4)-gas atomization.

11. The method of claim **10**, further comprising:

preparing molten silicon;

forcing the molten silicon through a nozzle;

directing a high-velocity gas stream at the molten silicon, the high-velocity gas stream comprising at least one gas selected from gases including helium (He) and argon (Ar) to break the molten silicon into silicon particles to form the powdered silicon; and

depositing silane on the silicon particles.

12. The method of claim **1**, wherein the powdered silicon is formed by plasma rotation electrode processing (PREP).

13. The method of claim **12**, further comprising:

melting an end of a silicon rod while the silicon rod is rotated, a rotational speed of the silicon rod being sufficient to create a centrifugal force to eject molten silicon from the silicon rod; and

solidifying the ejected molten silicon into silicon particles to from the powdered silicon.

14. The method of claim **13**, further comprising adjusting a morphology of the silicon particles by adjusting the rotational speed of the silicon rod.

15. The method of claim **1**, wherein the pre-determined temperature ramp-down rate is less than 5° C. per minute.

16. The method of claim **1**, further comprising:

preparing high-purity silicon by operations including:

placing silicon into a crucible;

increasing a temperature of the silicon at a pre-determined ramp-up rate;

at least partially melting the silicon with high-powered beam, the high-powered beam having a power sufficient to melt the silicon; and

decreasing the temperature of the silicon at a second pre-determined ramp-down rate.

17. The method of claim **16**, wherein the pre-determined ramp-up rate of temperature is determined by finite-element analysis including comparing heat flux and induced mechanical stresses in the silicon.

18. The method of claim **16**, wherein the temperature ramp-rate is 50 K per minute.

19. The method of claim **16**, wherein the pre-determined thickness of each layer in the layer-by-layer process is within a range from 30 μm to 50 μm.

20-29. (canceled)

30. A system for printing a fully dense component of a nonmetallic material, the system comprising:

a chamber under vacuum;

a first vertically movable plate arranged in the chamber to support a substrate;

a second vertically movable plate arranged adjacent to the first vertically movable plate, wherein the second vertically movable plate is configured to store a powder of the nonmetallic material and to dose the substrate with the powder prior to printing each layer of the nonmetallic material;

an electron beam generator configured to supply an electron beam; and

a controller configured to print a plurality of layers of the nonmetallic material on the substrate using the electron beam and to print a layer of the nonmetallic material on the plurality of layers to build the component on the plurality of layers.

31. The system of claim **30** wherein the nonmetallic material comprises spherical particles having a diameter within a range of 40-100 μm and wherein the diameter is measured using sieve analysis.

32. (canceled)

33. The system of claim **30** wherein the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

34. The system of claim **30** further comprising:

one or more meshes having holes of different diameters; and

a vibrating system configured to vibrate the one or more meshes;

wherein the powder is selected from a stock by passing the stock through the one or more meshes; and

wherein the selected powder comprises particles having a diameter within a range of 40-100 μm which is measured using sieve analysis.

35. The system of claim **30** further comprising a plate movement assembly configured to move the first vertically movable plate in a downward direction after printing each layer and to move the second vertically movable plate in an upward direction after printing each layer.

36-73. (canceled)

74. A method of printing a fully dense and crack free component of a nonmetallic material on a substrate made of the nonmetallic material in a chamber, the method comprising:

heating the substrate and a region of the chamber surrounding the substrate prior to printing a layer of the nonmetallic material on the substrate; and

printing the layer of the nonmetallic material on the substrate using an electron beam while continuing to heat the substrate and the region of the chamber surrounding the substrate during the printing.

75. The method of claim **74** wherein the nonmetallic material comprises particles having a diameter within a range of 40-100 μm, and wherein the diameter is measured using sieve analysis.

76. The method of claim **74** further comprising heating the substrate and the region of the chamber surrounding the substrate to a temperature greater than a ductile to brittle transition temperature of the nonmetallic material during the printing and annealing of the component.

77. The method of claim **74** further comprising after the printing, annealing and slow cooling the component in the chamber while continuing to heat the substrate and the region of the chamber surrounding the substrate.

78. The method of claim **74** further comprising after the printing, cooling the component by surrounding the component with a powder of the nonmetallic material.

79. The method of claim **74** further comprising thermally insulating the chamber using one or more of layers of one or more insulating materials.

80. The method of claim **74** wherein the nonmetallic material is selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

81. The method of claim **74** further comprising:
dosing the substrate with the nonmetallic material prior to printing each layer of the layer of the nonmetallic material; and
supplying the electron beam subsequent to the dosing to print each layer of the nonmetallic material.

82. The method of claim **74** further comprising heating a region of the chamber above the substrate during the printing of the component.

83. The method of claim **74** further comprising maintaining vacuum in the chamber.

84. The method of claim **74** further comprising maintaining a vacuum in the chamber.

85. The method of claim **74** further comprising:
selecting a powder of the nonmetallic material from a stock by passing the stock through one or more meshes having holes of different diameters and by vibrating the one or more meshes,
wherein the selected powder comprises particles having a diameter within a range of 40-100 μm, and wherein the diameter is measured using sieve analysis.

86. A component of a nonmetallic material printed using the method of claim **74** wherein the component is fully dense and lacking porosity and cracking.

87. A system comprising:
a chamber including:
an upper portion having an inlet to receive silicon powder, a carrier gas, and a dopant;
a middle portion connected to the upper portion; and
a third portion connected to the middle portion and having an outlet;
a coil arranged around the upper portion;
a power supply configured to supply power to the coil; and
a controller configured to:
control supply of the silicon powder, the carrier gas, and the dopant to the inlet; and
control the power supplied to the coil to generate plasma,
wherein the outlet outputs a spherical shaped, dense, and doped silicon powder.

88. The system of claim **87** wherein the middle portion has a greater cross-sectional area than the upper portion and wherein the third portion has a smaller cross-sectional area than the upper portion.

89. The system of claim **87** wherein the upper portion includes:
an inner tube;
a middle tube coaxially surrounding the inner tube; and
an outer tube defined by an outer wall of the middle tube and an inner wall of the upper portion;
wherein the inner, middle, and the outer tubes extend vertically downwards from a top end of the upper portion to a midpoint of the upper portion; and
wherein the coil is arranged around the upper portion between the midpoint of the upper portion and a bottom end of the upper portion.

90. The system of claim **89** wherein the silicon powder is supplied to the inner tube, the system further comprising:
a first gas source to supply the carrier gas to mix with the silicon powder;
a second gas source to supply the dopant to the middle tube; and
a third gas source to supply a sheath gas to the outer tube.

91. A method of building a component for a substrate processing system, the method comprising:
arranging first and second subcomponents of the component in a thermally insulated zone in a chamber under vacuum;
heating the first and second subcomponents in the thermally insulated zone to a predetermined temperature;
bonding a first end of the first subcomponent to a second end of the second subcomponent by partially melting material at the first and second ends using an electron beam followed by solidifying the melted material;
annealing the bonded first and second subcomponents to form the component;
cooling the formed component to a first temperature at a first rate; and
cooling the formed component to a second temperature at a second rate,
wherein the second temperature is less than the first temperature; and
wherein the first rate is slower than the second rate.

92. The method of claim **91** wherein the component is made of a nonmetallic material selected from a group consisting of silicon, silicon carbide, alumina, and ceramics.

93. The method of claim **91** further comprising bonding the first and second subcomponents without using any additional material.

94. The method of claim **91** further comprising cleaning mating surfaces of the first and second ends before the melting.

95. The method of claim **91** further comprising grinding excess material from the component and cleaning the component.

96-125. (canceled)

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