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(54) **HIGH-POWER DENSITY RF REMOTE PLASMA SOURCE APPARATUS**

(71) Applicant: **Applied Materials, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Mehran Moalem**, Fremont, CA (US); **Kartik Ramaswamy**, San Jose, CA (US)

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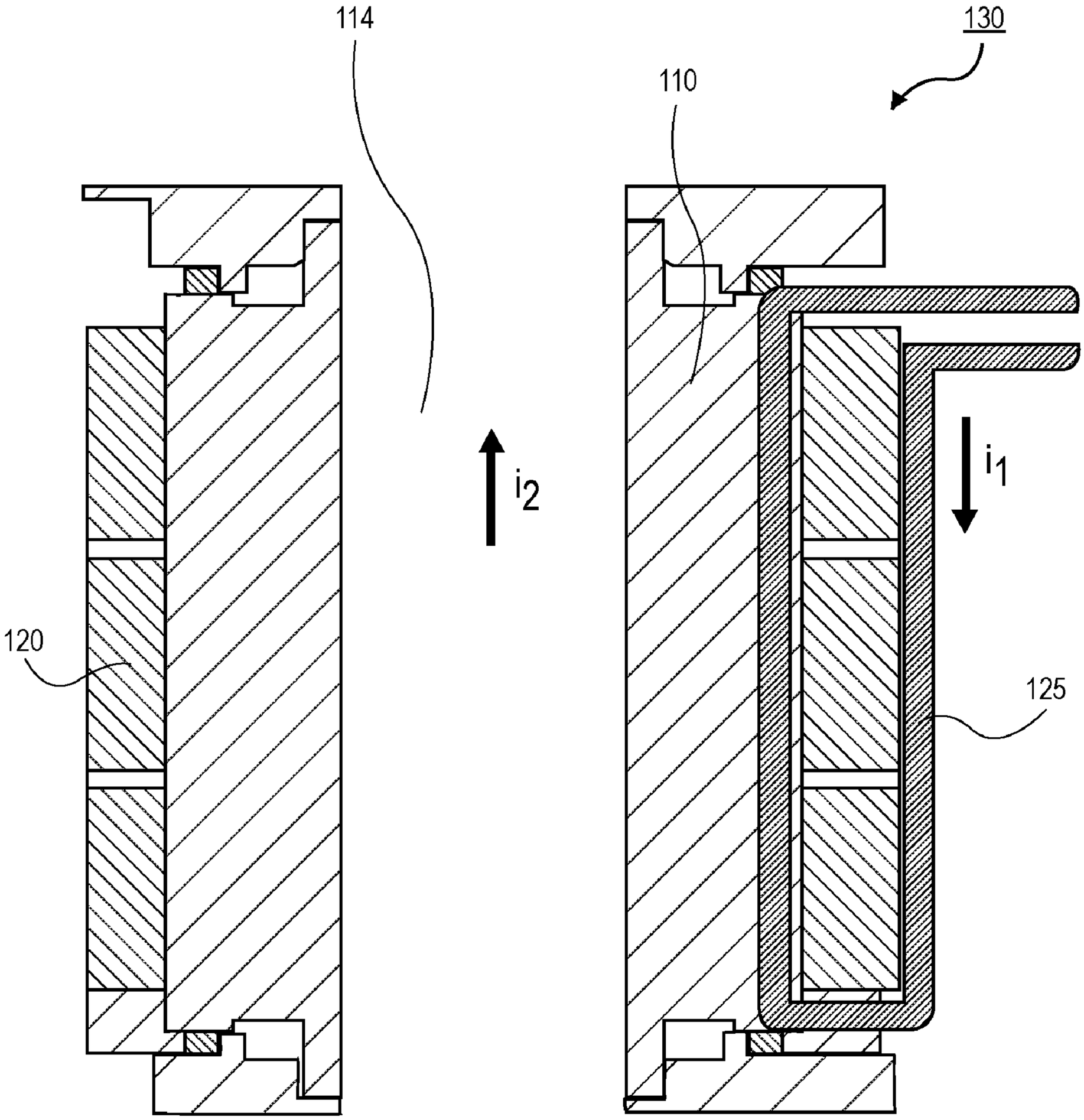
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(57) **ABSTRACT**

Embodiments disclosed herein include a plasma source. In an embodiment, the plasma source includes a plurality of plasma legs connected to each other by corner connectors. In an embodiment, each plasma leg comprises a conductive shell, a magnetic layer around the conductive shell, and a primary coil in the magnetic layer.



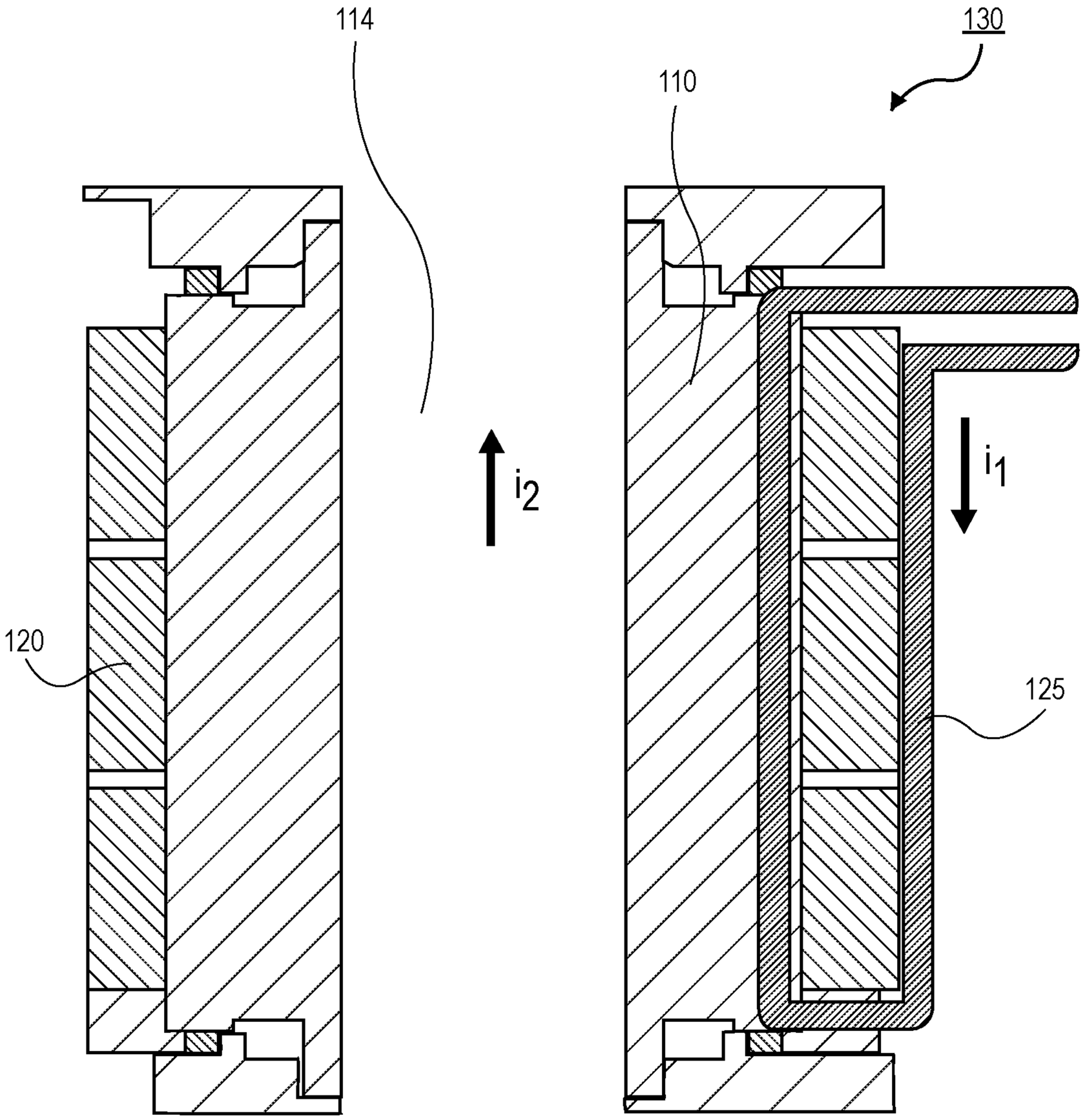


FIG. 1

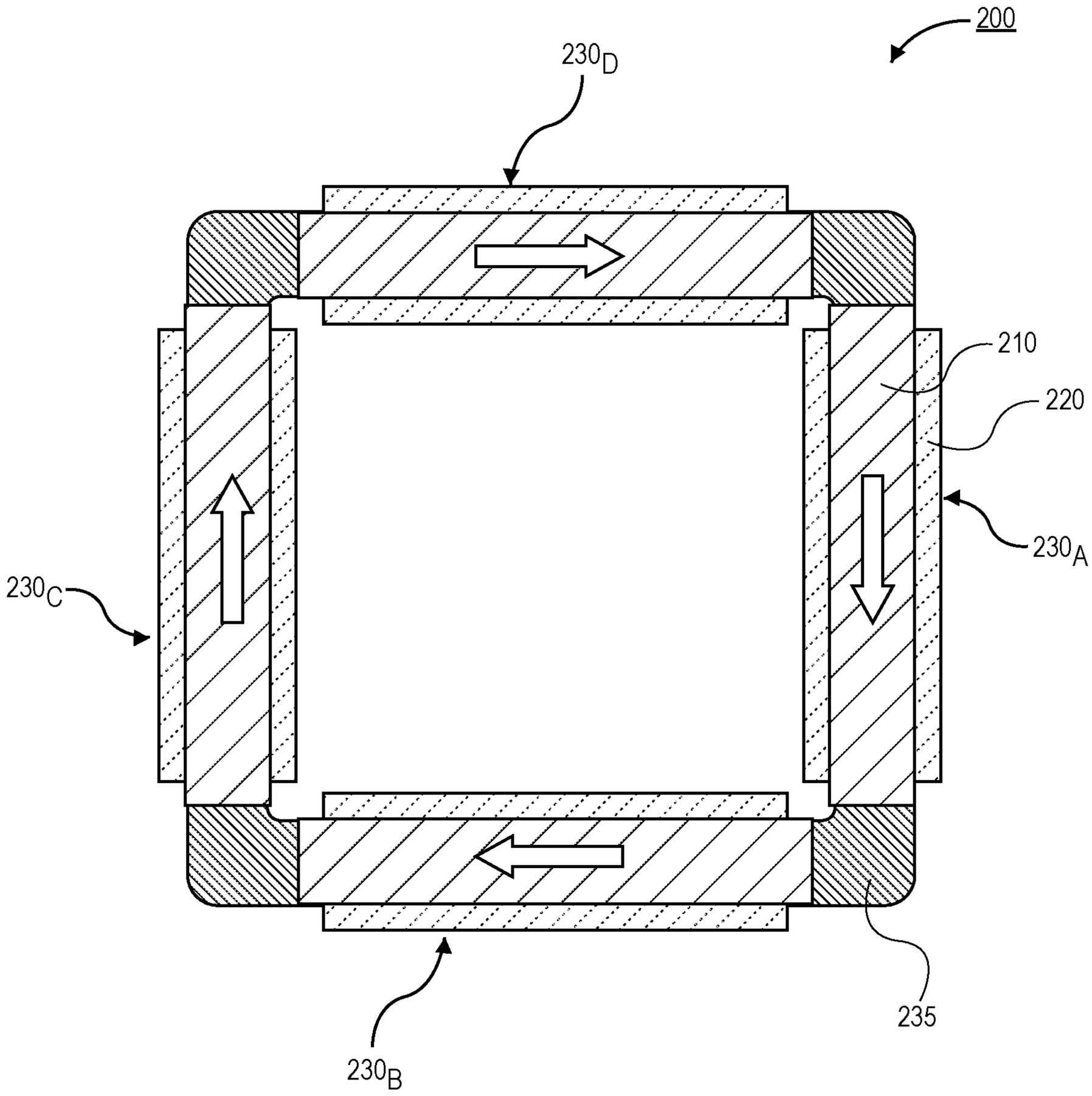


FIG. 2

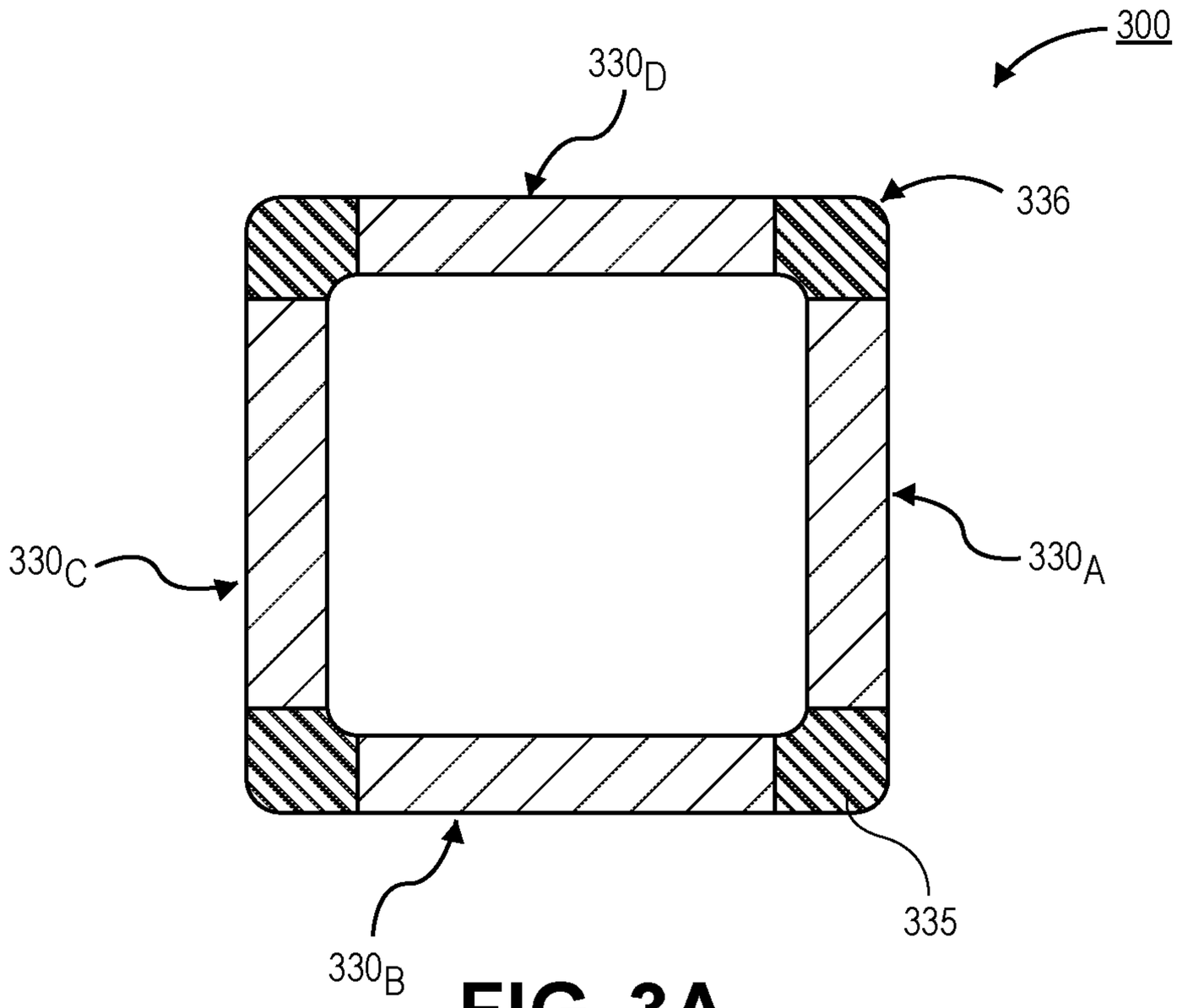

300
330D
336
330C
330A
335
330B

FIG. 3A

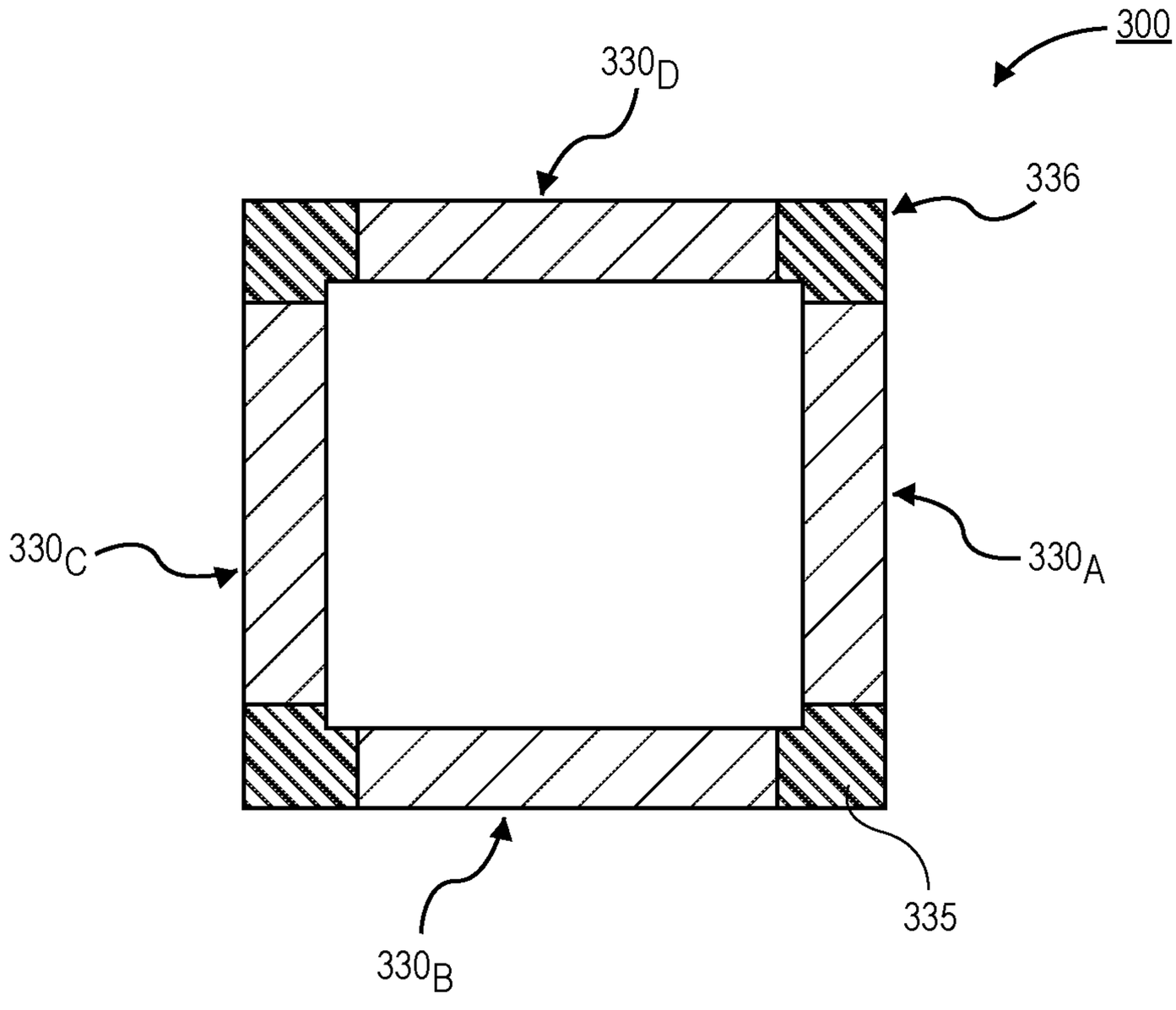

300
330D
336
330C
330A
335
330B

FIG. 3B

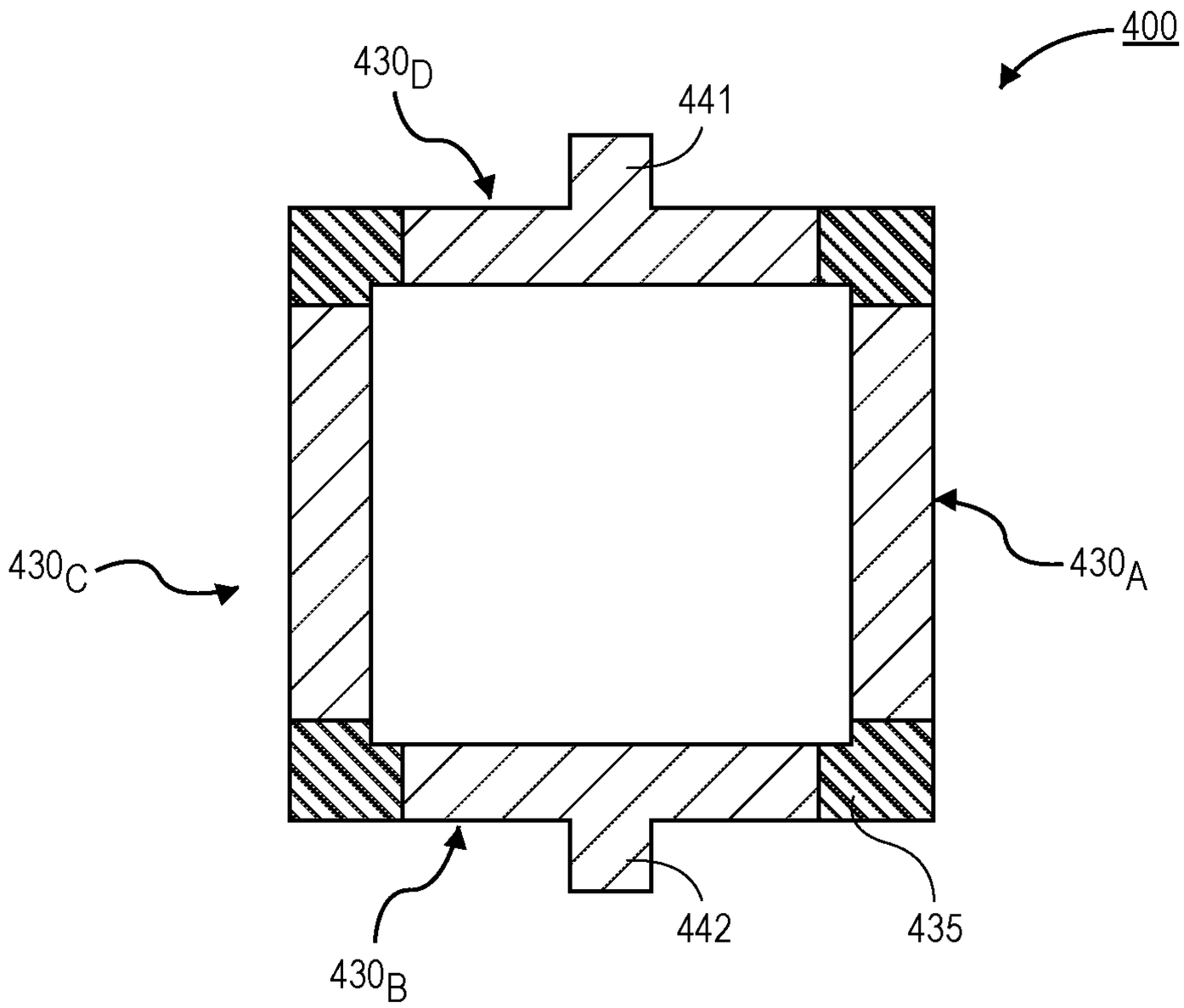

400
430D
441
430C
430A
442
435
430B

FIG. 4A

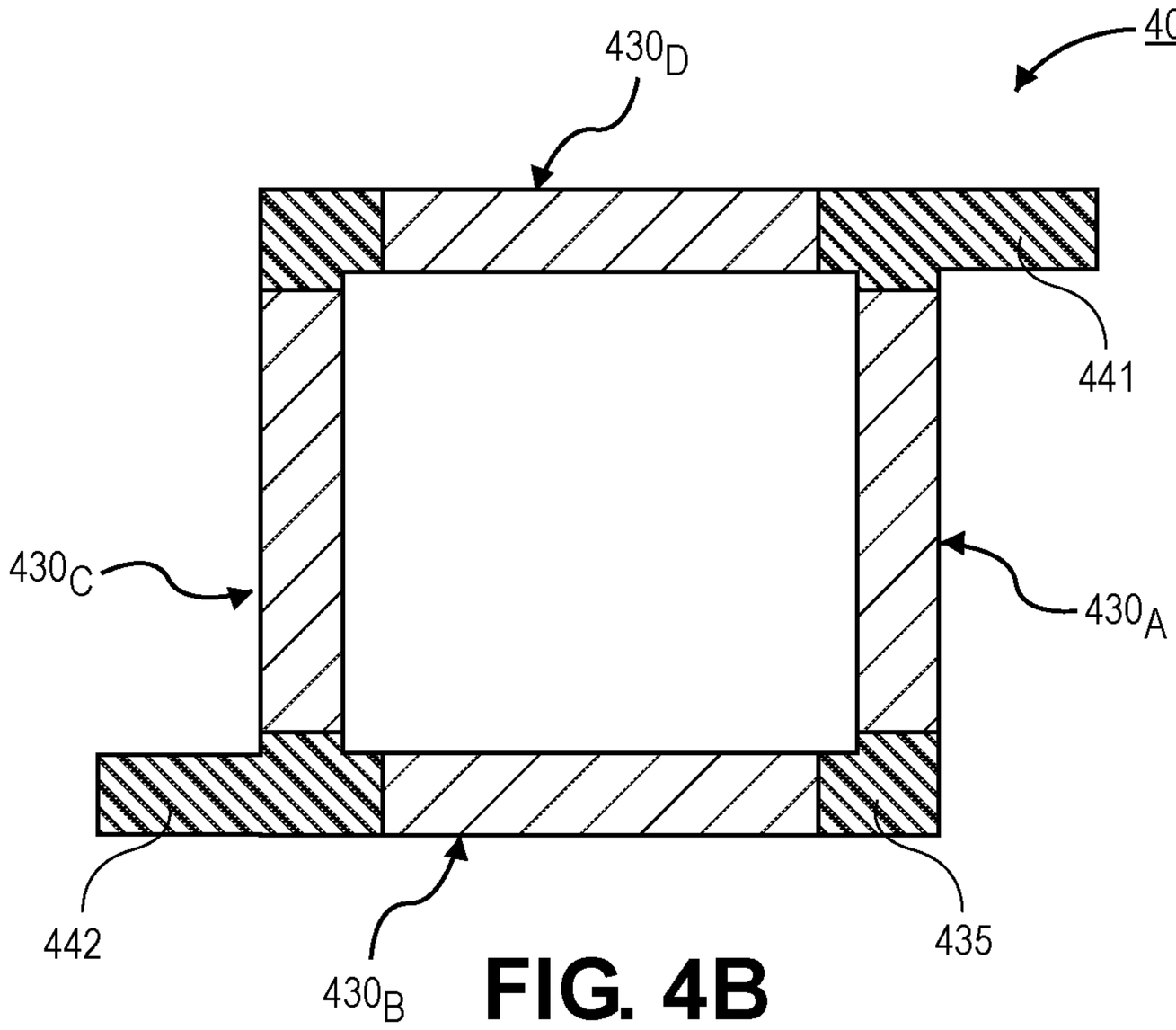

400
430D
441
430C
430A
442
435
430B

FIG. 4B

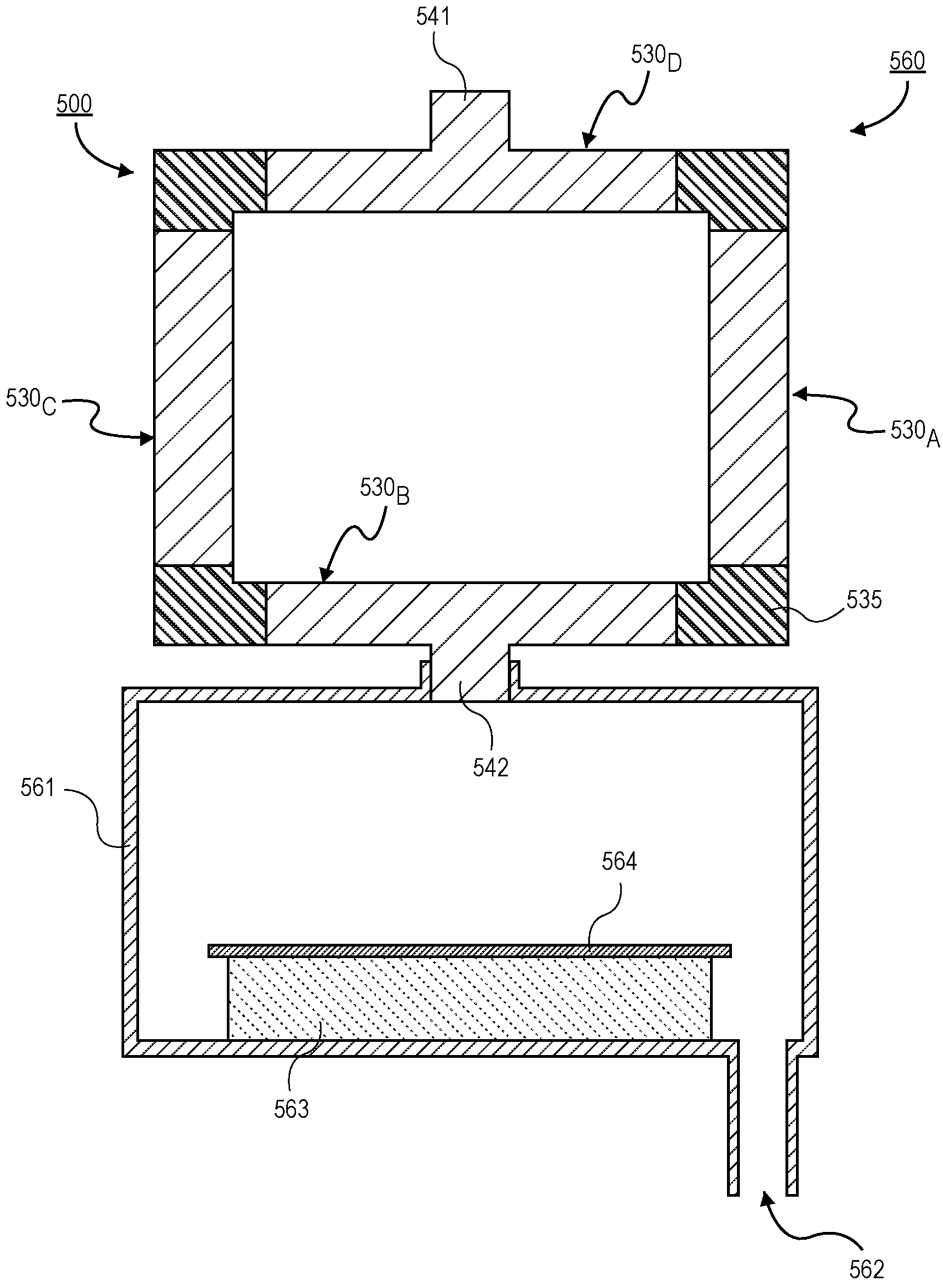


FIG. 5

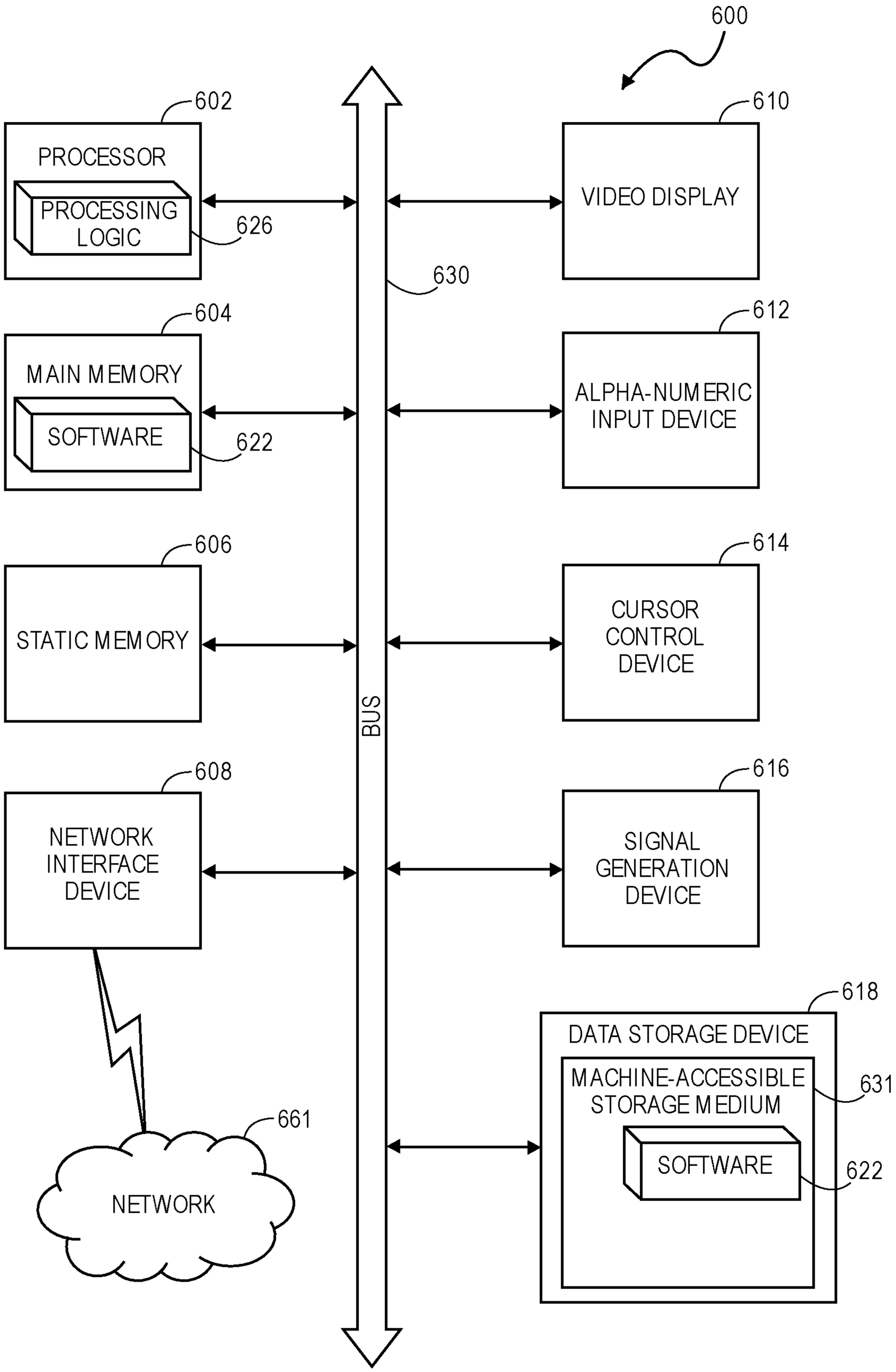

600
602
PROCESSOR
PROCESSING LOGIC
626
604
MAIN MEMORY
SOFTWARE
622
606
STATIC MEMORY
608
NETWORK INTERFACE DEVICE
661
NETWORK
BUS
630
610
VIDEO DISPLAY
612
ALPHA-NUMERIC INPUT DEVICE
614
CURSOR CONTROL DEVICE
616
SIGNAL GENERATION DEVICE
618
DATA STORAGE DEVICE
MACHINE-ACCESSIBLE STORAGE MEDIUM
631
SOFTWARE
622

FIG. 6

HIGH-POWER DENSITY RF REMOTE PLASMA SOURCE APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/238,623, filed on Aug. 30, 2021, the entire contents of which are hereby incorporated by reference herein.

Background

1) FIELD

[0002] Embodiments of the present disclosure pertain to the field of semiconductor processing and, in particular, to remote plasma systems for generating high-power and high-density microwave plasmas.

2) Description of Related Art

[0003] Semiconductor deposition systems require frequent chamber cleaning to clear buildup of material on the chamber walls. The most efficient process typically used includes an NF_3 remote plasma clean. In such cleaning processes, the NF_3 is broken down in the plasma to generate atomic fluorine. The atomic fluorine flows from the remote plasma source to the chamber. Atomic fluorine is highly reactive and reacts with the material deposited on the chamber walls to form a volatile product that can be removed through a vacuum exhaust system. Typically, such remote plasma cleaning processes require high power and high flow rates of the NF_3 due to low utilization rates. Accordingly, the process can be expensive and wasteful.

SUMMARY

[0004] Embodiments disclosed herein include a plasma source. In an embodiment, the plasma source includes a plurality of plasma legs connected to each other by corner connectors. In an embodiment, each plasma leg comprises a conductive shell, a magnetic layer around the conductive shell, and a primary coil in the magnetic layer.

[0005] Embodiments disclosed herein may also comprise a toroidal remote plasma source. In an embodiment, the toroidal remote plasma source comprises a first plasma leg, a second plasma leg coupled to the first plasma leg by a first corner connector, a third plasma leg coupled to the second plasma leg by a second corner connector, and a fourth plasma leg coupled to the third plasma leg by a third corner connector. In an embodiment, the fourth plasma leg is also coupled to the first plasma leg by a fourth corner connector.

[0006] Embodiments disclosed herein also comprise a plasma processing tool. In an embodiment, the plasma processing tool comprises a chamber, and a remote plasma source coupled to the chamber. In an embodiment, the remote plasma source comprises a plurality of plasma legs connected to each other by corner connectors. In an embodiment, each plasma leg comprises a conductive shell, a magnetic layer around the conductive shell, and a primary coil in the magnetic layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a cross-sectional illustration of a plasma leg in a toroidal plasma source, where the plasma leg comprises a conductive shell, a magnetic layer, and a primary coil, in accordance with an embodiment.

[0008] FIG. **2** is a plan view illustration of a toroidal plasma source with a plurality of plasma legs that are coupled together by corner connectors, in accordance with an embodiment.

[0009] FIG. **3**A is a plan view illustration of a toroidal plasma source with a plurality of plasma legs that are coupled together by rounded corner connectors, in accordance with an embodiment.

[0010] FIG. **3**B is a plan view illustration of a toroidal plasma source with a plurality of plasma legs that are coupled together by corner connectors with sharp corners, in accordance with an embodiment.

[0011] FIG. **4**A is a plan view illustration of a toroidal plasma source with a gas inlet and a gas outlet that are coupled to opposite plasma legs, in accordance with an embodiment.

[0012] FIG. **4**B is a plan view illustration of a toroidal plasma source with a gas inlet and a gas outlet that are coupled to opposite corner connectors, in accordance with an embodiment.

[0013] FIG. **5** is a cross-sectional illustration of a processing tool with a toroidal remote plasma system with a plurality of plasma legs that are coupled together by corner connectors, in accordance with an embodiment.

[0014] FIG. **6** illustrates a block diagram of an exemplary computer system, in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0015] Remote plasma systems for generating high-power and high-density microwave plasmas are described herein. In the following description, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present disclosure. It will be apparent to one skilled in the art that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known aspects are not described in detail in order to not unnecessarily obscure embodiments of the present disclosure. Furthermore, it is to be understood that the various embodiments shown in the Figures are illustrative representations and are not necessarily drawn to scale.

[0016] As noted above, plasma cleaning processes typically utilize remote plasma systems. However, existing systems are limited in gas utilization efficiency and require high power to achieve a desired gas breakdown efficiency. Accordingly, embodiments disclosed herein include remote plasma sources that have improved gas utilization efficiency and require lower power for the same breakdown efficiency. In an embodiment, the RF energy is focused to a smaller volume than in standard remote plasma systems. The focusing of the energy results in an increase in the power density. Improved power density enables a more efficient process and better dissociating efficiency in breaking feed gasses into radical species. Accordingly, remote plasma systems disclosed herein require lower power for the same breakdown efficiency, lower flow rates of gas into the remote plasma system, and lower costs for equipment and consumables.

[0017] In a particular embodiment, the remote plasma system is a toroidal plasma assembly. The toroidal plasma assembly includes four legs (top, bottom, and sides) where

plasma is generated in each leg. The four plasma legs may be coupled together by grounded corner fittings. Each leg may include a primary coil in order to induce the plasma. The current through each primary coil may be controlled in order to modify the plasma characteristics. Additionally, the primary coils may be electrically in parallel, electrically in series, or some combination of electrically in parallel and electrically in series. Additionally, the gas inlet and gas outlet may be oriented at different locations. In one embodiment, the gas inlet is centered on the top plasma leg and the gas outlet is centered on the bottom plasma leg. Such an embodiment may provide more symmetric gas flow through the remote plasma source. In other embodiments, the gas inlet and the gas outlet may be connected to the grounded corner fittings. Such an embodiment may provide ease of assembly since the inlet and outlet do not need to pass through the magnetic core and primary coil of each plasma leg.

[0018] Referring now to FIG. **1**, a cross-sectional illustration of a single leg **130** of a toroidal remote plasma system is shown, in accordance with an embodiment. In an embodiment, the plasma leg includes a conductive shell **110** with a top opening and a bottom opening. A plasma zone **114** may be provided within the conductive shell **110**. In an embodiment, a magnetic layer **120** is provided around the conductive shell **110**. The magnetic layer **120** may be any suitable magnetic material, such as a ferrite. It is to be appreciated that a plasma may be struck in the plasma zone **114** within the conductive shell **110**. The magnetic layer **120** helps to confine the generated plasma in the volume **114**. For example, a microwave induced plasma may be struck within the plasma zones **114**. A primary coil **125** may be provided through the magnetic layer **120**. The primary coil **125** may be supplied a current ii to induce the plasma. A secondary current i**2** may be generated in the plasma zone **114** as indicated by the arrow. In an embodiment, the conductive shell **110** is configured to be at a floating voltage. In other embodiments, the conductive shell **110** may be held at a desired voltage.

[0019] Referring now to FIG. **2** an illustration of a toroidal remote plasma system **200** is shown, in accordance with an embodiment. As shown, the toroidal remote plasma system **200** comprises a plurality of plasma legs **230**. For example, four plasma legs $\mathbf{230}_A$-$\mathbf{230}_D$ are connected to each other by grounded corner connectors **235**. Each of the plasma legs $\mathbf{230}_A$-$\mathbf{230}_D$ may be substantially similar to the plasma leg **130** described in greater detail above. For example, each plasma leg **230** may include a conductive shell **210** and a magnetic layer **220** around the conductive shell **210**.

[0020] While not show for simplicity, each plasma leg **230** may also comprise a primary coil to induce plasma in the conductive shell **210**. In some embodiments, each of the plasma legs **230** may have an electrically isolated primary coil. As such, the plasma power within each of the plasma legs **230** may be individually controllable. In other embodiments, the primary coils for each of the conductive shells **210** may be electrically connected in parallel. In yet another embodiment, the primary coils for each of the plasma legs **230** may be connected in series. Embodiments may also include a combination of primary coils that are connected in parallel and in series. As shown by the arrows, the primary coils may induce a secondary current within the conductive shells **210**. The secondary current in each conductive shell may all be in the same direction. For example, in FIG. **2**, the arrows of the secondary current point in a clockwise direction.

[0021] It is to be appreciated that a true toroidal plasma may be generated in the remote plasma system **200**. That is, the plasma may be generated at the top and bottom legs $\mathbf{230}_B$ and $\mathbf{230}_D$ in addition to the side legs $\mathbf{230}_A$ and $\mathbf{230}_C$. This is in contrast to existing so called "toroidal" plasmas that only have plasma generation on the side legs. In such architectures, the top and bottom regions provide fluidic coupling between the side legs, but there are no coils to actively induce plasma at the top and bottom.

[0022] Referring now to FIG. **3**A, an illustration of the toroidal remote plasma system **300** is shown, in accordance with an embodiment. As shown, the remote plasma system **300** comprises a plurality of plasma legs $\mathbf{330}_A$-$\mathbf{330}_D$ that are coupled together by grounded corner connectors **335**. Each plasma leg **330** may be substantially similar to the plasma legs described in greater detail above. For example, each plasma leg **330** may comprise a conductive shell with a magnetic layer around the conductive shell. Primary coils may also be provided around the plasma leg **330** to induce the plasma.

[0023] In the illustrated embodiment, the corner connectors **335** are held at a ground potential. In an embodiment, the corner connectors **335** may have rounded corner surfaces **336**. The rounded corner surfaces **336** may improve gas flow around the remote plasma system **200**. Additionally, rounded corners may result in less damage. As such, the lifespan of the remote plasma system **200** may be improved. However, it is to be appreciated that embodiments are not limited to rounded corners. For example, in FIG. **3**B, the grounded corner connectors **335** have sharp corner surfaces **336**.

[0024] Referring now to FIG. **3**B, an illustration of a remote plasma system **300** is shown, in accordance with an additional embodiment. Similar to the embodiment in FIG. **3**A, the remote plasma system **300** comprises a plurality of plasma legs $\mathbf{330}_A$-$\mathbf{330}_D$ that are coupled together by corner connectors **335**. In an embodiment, the corner connectors **335** are configured to be held at a ground potential. However, instead of having rounded corner surfaces **336**, the corner surfaces **336** are sharp corners.

[0025] Referring now to FIG. **4**A, an illustration of a toroidal remote plasma system **400** is shown, in accordance with an embodiment. In an embodiment, the toroidal remote plasma system **400** may comprise a plurality of plasma legs $\mathbf{430}_A$-$\mathbf{430}_D$ that are coupled together by connectors **435**. In the illustrated embodiment, the connectors **435** may have sharp corners (similar to the embodiment shown in FIG. **3**B). In other embodiments, the connectors **435** may have rounded corners (similar to the embodiment shown in FIG. **3**A). The connectors **435** may be configured to be held at a ground potential.

[0026] In an embodiment, a gas inlet **441** and a gas outlet **442** are coupled to the toroidal remote plasma system **400**. In an embodiment, the gas inlet **441** is coupled to the top plasma leg $\mathbf{430}_D$, and the gas outlet **442** is coupled to the bottom plasma leg $\mathbf{430}_B$. Such coupling allows for a more symmetric flow of gasses through the remote plasma system **400**. For example, approximately half of the gas will flow from the top plasma leg $\mathbf{430}_D$ to the right plasma leg $\mathbf{430}_A$ and to the bottom plasma leg $\mathbf{430}_B$, and the other half of the gas will flow from the top plasma leg $\mathbf{430}_D$ to the left plasma leg $\mathbf{430}_C$ and to the bottom plasma leg $\mathbf{430}_B$.

[0027] While not shown in FIG. **4**A, it is to be appreciated that magnetic layers and primary coils are provided around each of the plasma legs **430**. Accordingly, the gas inlet **441** and the gas outlet **442** need to be routed through the magnetic layers and the primary coils in order to access the top plasma leg $\mathbf{430}_D$ and the bottom plasma leg $\mathbf{430}_B$. Such routing may increase the complexity of the remote plasma system **400**.

[0028] Accordingly, an embodiment where the gas inlet **441** and the gas outlet **442** are coupled to corner connectors **435** is shown in FIG. **4**B. Coupling to the corner connectors **435** instead of the plasma legs **430** eliminates the need to pass through the magnetic layers and the primary coils. As such, the construction of the remote plasma system **400** may be simplified compared to the embodiment shown in FIG. **4**A.

[0029] Referring now to FIG. **5**, a cross-sectional illustration of a processing tool **560** is shown, in accordance with an embodiment. In an embodiment, the processing tool **560** comprises a processing chamber **561**. The processing chamber **561** may be a chamber that is capable of supporting a sub-atmospheric pressure during the processing of substrate **564**. The chamber **561** may be fluidically coupled to a pump through an exhaust system **562**. In an embodiment, the substrate **564** may be supported and secured by a chuck **563**, a pedestal or the like. In an embodiment, the substrate **564** is a semiconductor substrate, such as a silicon wafer or a wafer of another semiconductor material. In other embodiments, the substrate **564** may comprise a glass substrate, an organic substrate, or any other substrate typical of semiconductor manufacturing processes.

[0030] In an embodiment, the processing chamber **561** is used as a material deposition chamber. For example, material may be deposited onto a surface of the substrate **564**. In an embodiment, the processing chamber **561** is a chemical vapor deposition (CVD) chamber, an atomic layer deposition (ALD) chamber, or a physical vapor deposition (PVD) chamber. In other embodiments, the processing chamber **561** is an etching chamber. That is, material is removed from the surface of the substrate **564**. During deposition or etching processes, material may deposit along the interior surfaces of the chamber **561**. As such, periodic chamber **561** cleaning may be necessary.

[0031] In an embodiment, the chamber cleaning may be implemented with a remote plasma source **500**. The remote plasma source **500** may be substantially similar to any of the plasma sources described herein. For example, the plasma source **500** may comprise be a toroidal remote plasma source **500**. In such an embodiment, the plasma source **500** may comprise a plurality of plasma legs $\mathbf{530}_A$-$\mathbf{530}_D$. Each of the plasma legs **530** may comprise a conductive shell that is surrounded by a magnetic layer and a primary coil for inducing a plasma in the conductive shell. The magnetic layer and the primary coil are omitted from FIG. **5** for simplicity. However, it is to be appreciated that the magnetic layers and the primary coils may be similar to the embodiment shown and described with respect to FIG. **1** above.

[0032] In an embodiment, each of the plasma legs **530** may be coupled to each other by corner connectors **535**. The corner connectors **535** may be configured to be held at a ground potential in some embodiments. In the illustrated embodiment, the corner connectors have sharp corners. However, in other embodiments, the corner connectors **535** may have rounded corners, similar to the embodiment shown in FIG. **3**A.

[0033] In an embodiment, the plasma source **500** may comprise a gas inlet **541** and a gas outlet **542**. The gas inlet **541** and the gas outlet **542** may be coupled to plasma legs **530**, as shown in FIG. **5**. In the illustrated embodiment, the gas inlet **541** is coupled to a top plasma leg $\mathbf{530}_D$, and the gas outlet **542** is coupled to a bottom plasma leg $\mathbf{530}_B$. The gas outlet **542** may be fluidically coupled to the chamber **561**. The configuration with the gas inlet **541** and the gas outlet **542** on opposite plasma legs **530** may provide a symmetric flow of gasses through the plasma source **500**.

[0034] However, in other embodiments, the gas inlet **541** and the gas outlet **542** may be coupled to corner connectors **535** instead of the plasma legs. Such an embodiment may be similar to the construction shown in FIG. **4**B. Coupling the gas inlet **541** and the gas outlet **542** to the corner connectors **535** may simplify the construction of the plasma source **500** since the gas inlet **541** and the gas outlet **542** do not need to pass through the magnetic layer or primary coil around each of the plasma legs **530**.

[0035] FIG. **6** illustrates a diagrammatic representation of a machine in the exemplary form of a computer system **600** within which a set of instructions, for causing the machine to perform any one or more of the methodologies described herein, may be executed. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet PC, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies described herein.

[0036] The exemplary computer system **600** includes a processor **602**, a main memory **604** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM) or Rambus DRAM (RDRAM), etc.), a static memory **606** (e.g., flash memory, static random access memory (SRAM), MRAM, etc.), and a secondary memory **618** (e.g., a data storage device), which communicate with each other via a bus **630**.

[0037] Processor **602** represents one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processor **602** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processor **602** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array

(FPGA), a digital signal processor (DSP), network processor, or the like. Processor **602** is configured to execute the processing logic **626** for performing the operations described herein.

[0038] The computer system **600** may further include a network interface device **608**. The computer system **600** also may include a video display unit **610** (e.g., a liquid crystal display (LCD), a light emitting diode display (LED), or a cathode ray tube (CRT)), an alphanumeric input device **612** (e.g., a keyboard), a cursor control device **614** (e.g., a mouse), and a signal generation device **616** (e.g., a speaker).

[0039] The secondary memory **618** may include a machine-accessible storage medium (or more specifically a computer-readable storage medium) **632** on which is stored one or more sets of instructions (e.g., software **622**) embodying any one or more of the methodologies or functions described herein. The software **622** may also reside, completely or at least partially, within the main memory **604** and/or within the processor **602** during execution thereof by the computer system **600**, the main memory **604** and the processor **602** also constituting machine-readable storage media. The software **622** may further be transmitted or received over a network **620** via the network interface device **608**.

[0040] While the machine-accessible storage medium **632** is shown in an exemplary embodiment to be a single medium, the term "machine-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "machine-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present disclosure. The term "machine-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

[0041] In accordance with an embodiment of the present disclosure, a machine-accessible storage medium has instructions stored thereon which cause a data processing system to perform a method of cleaning a processing chamber using a toroidal remote plasma source with a plurality of plasma legs that are coupled together by corner connectors.

[0042] Thus, methods for chamber cleaning with a remote plasma have been disclosed.

What is claimed is:

1. A plasma source, comprising:

a plurality of plasma legs connected to each other by corner connectors, wherein each plasma leg comprises:

a conductive shell;

a magnetic layer around the conductive shell; and

a primary coil in the magnetic layer.

2. The plasma source of claim **1**, wherein the plurality of plasma legs comprises four plasma legs.

3. The plasma source of claim **2**, wherein the primary coils of each plasma leg are electrically isolated from each other.

4. The plasma source of claim **2**, wherein the primary coils of each plasma leg are connected electrically in series.

5. The plasma source of claim **2**, wherein the primary coils of each plasma leg are connected electrically in parallel.

6. The plasma source of claim **1**, wherein the corner connectors are configured to be at a ground potential.

7. The plasma source of claim **6**, wherein the conductive shells are configured to be at a floating potential.

8. The plasma source of claim **1**, wherein the corner connectors have a rounded corner surface.

9. The plasma source of claim **1**, wherein the corner connectors have a sharp corner surface.

10. The plasma source of claim **1**, further comprising:

a gas inlet to the plasma source; and

a gas outlet from the plasma source.

11. The plasma source of claim **10**, wherein the gas inlet is coupled to a first plasma leg, and wherein the gas outlet is coupled to a second plasma leg.

12. The plasma source of claim **10**, wherein the gas inlet is coupled to a first corner connector, and wherein the gas outlet is coupled to a second corner connector.

13. A toroidal remote plasma source, comprising:

a first plasma leg;

a second plasma leg coupled to the first plasma leg by a first corner connector;

a third plasma leg coupled to the second plasma leg by a second corner connector; and

a fourth plasma leg coupled to the third plasma leg by a third corner connector, and wherein the fourth plasma leg is also coupled to the first plasma leg by a fourth corner connector.

14. The toroidal remote plasma source of claim **13**, wherein each plasma leg is surrounded by a magnetic layer and a primary coil.

15. The toroidal remote plasma source of claim **14**, wherein the primary coils are configured to induce secondary currents within the plasma legs that are all oriented in the same direction around the toroidal remote plasma source.

16. The toroidal remote plasma source of claim **13**, wherein the corner connectors have rounded corner surfaces.

17. The toroidal remote plasma source of claim **13**, further comprising:

a gas inlet; and

a gas outlet.

18. The toroidal remote plasma source of claim **17**, wherein the gas inlet is coupled to the first plasma leg, and wherein the gas outlet is coupled to the third plasma leg.

19. A plasma processing tool, comprising:

a chamber; and

a remote plasma source coupled to the chamber, wherein the remote plasma source comprises:

a plurality of plasma legs connected to each other by corner connectors, wherein each plasma leg comprises:

a conductive shell;

a magnetic layer around the conductive shell; and

a primary coil in the magnetic layer.

20. The plasma processing tool of claim **19**, wherein the plurality of plasma legs comprises four plasma legs.

* * * * *