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(54) **METHODS FOR TREATING EXHAUST GAS IN A PROCESSING SYSTEM**

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(57) **ABSTRACT**

Methods and apparatus for treating an exhaust gas in a foreline of a substrate processing system are provided herein. In some embodiments, a method for treating an exhaust gas in an exhaust conduit of a substrate processing system includes: flowing an exhaust gas from a process chamber into a plasma source via a foreline; injecting a reagent into the foreline; forming a plasma in the plasma source from the exhaust gas and the reagent; and injecting a cleaning gas into the foreline, wherein the cleaning gas and the reagent are different gases.

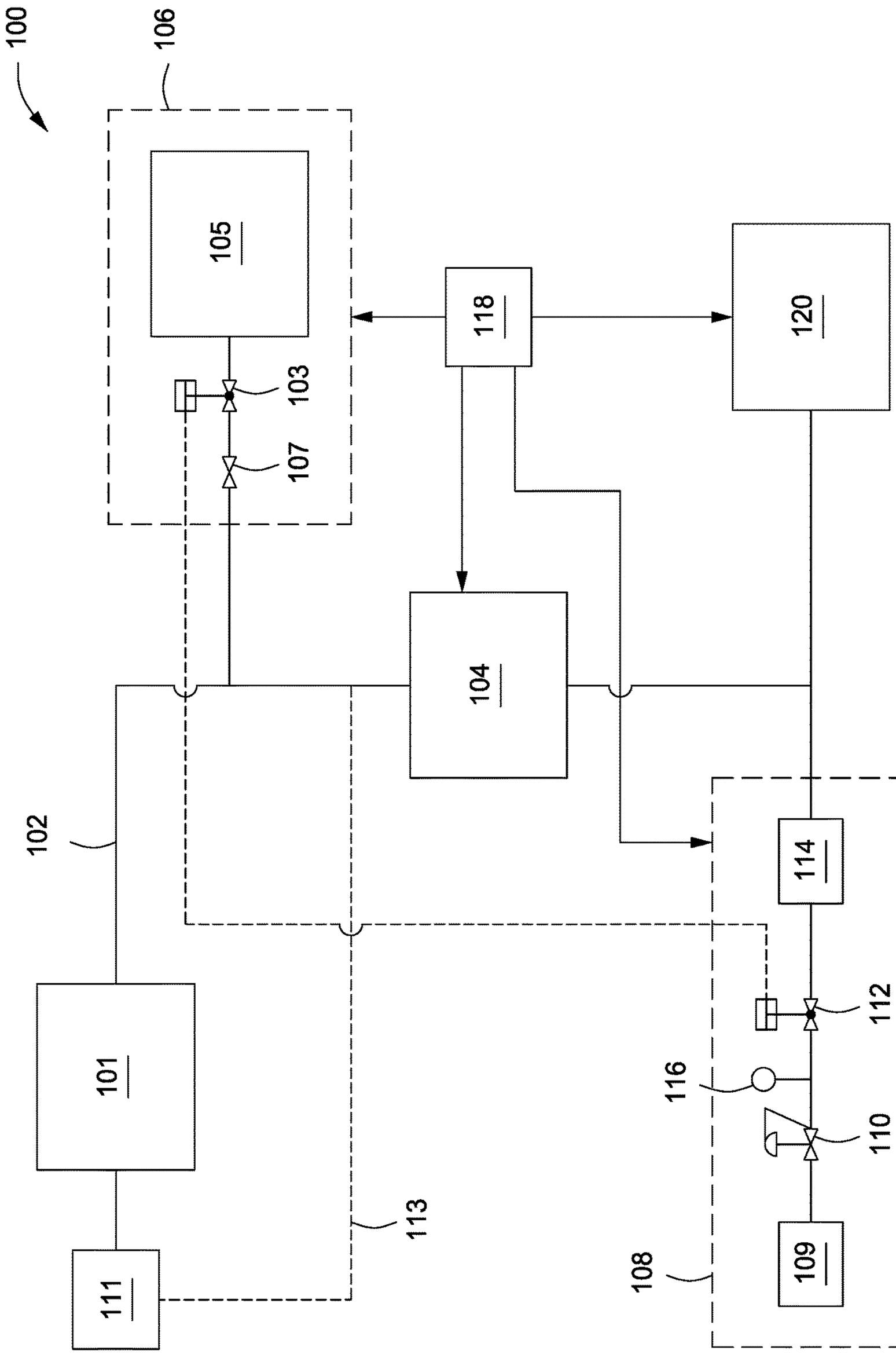

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FIG. 1

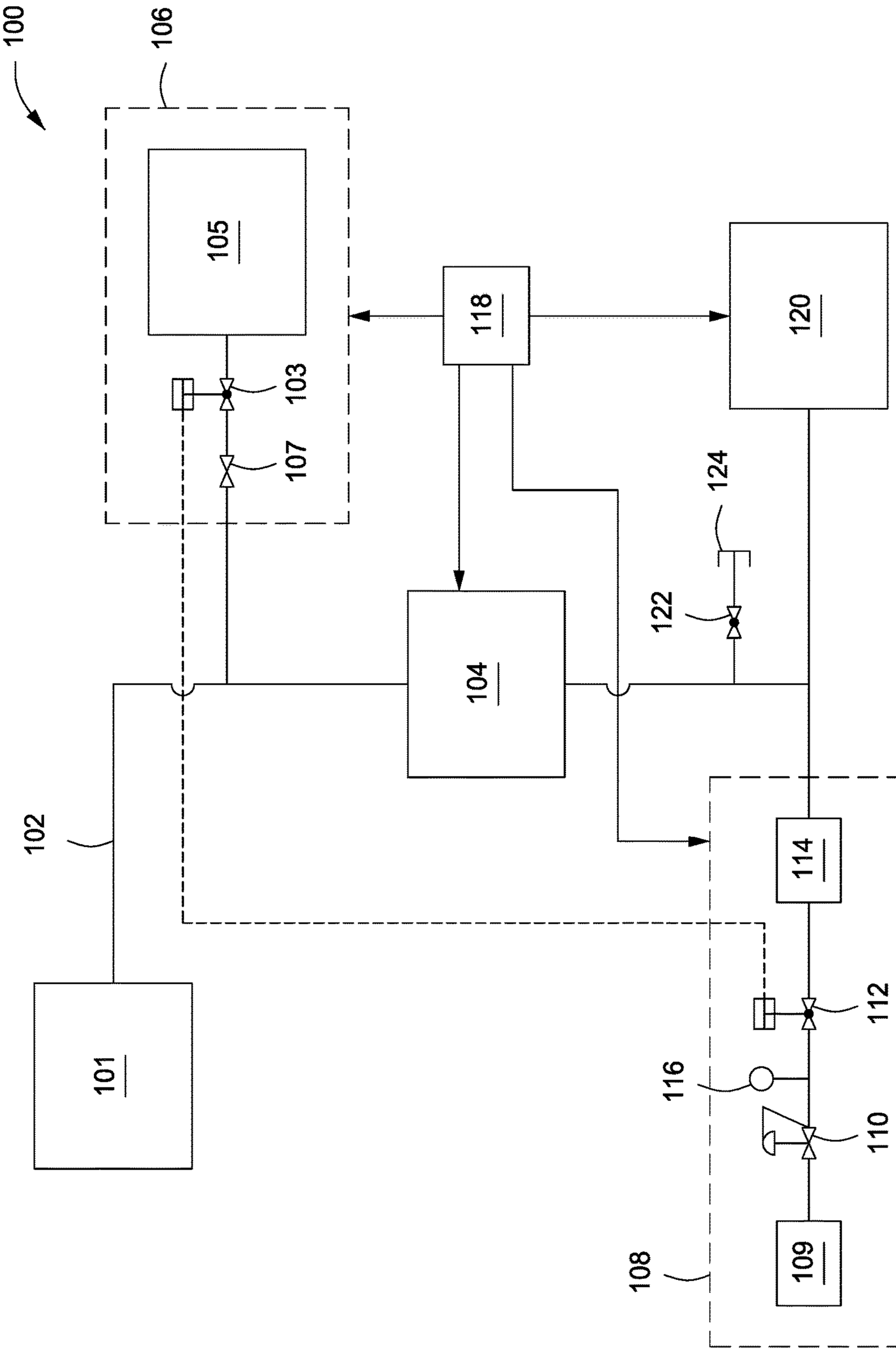

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FIG. 2

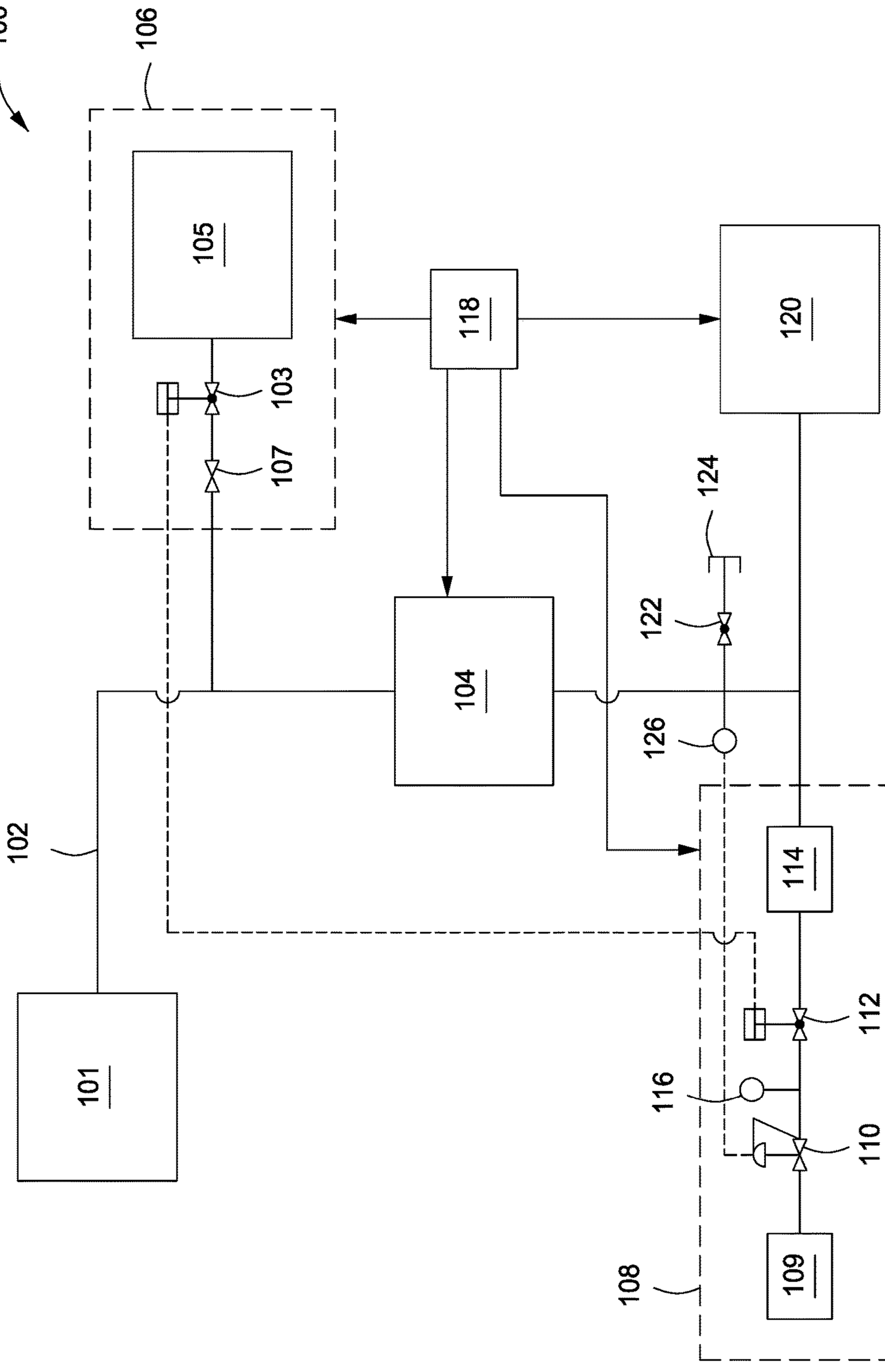

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FIG. 3

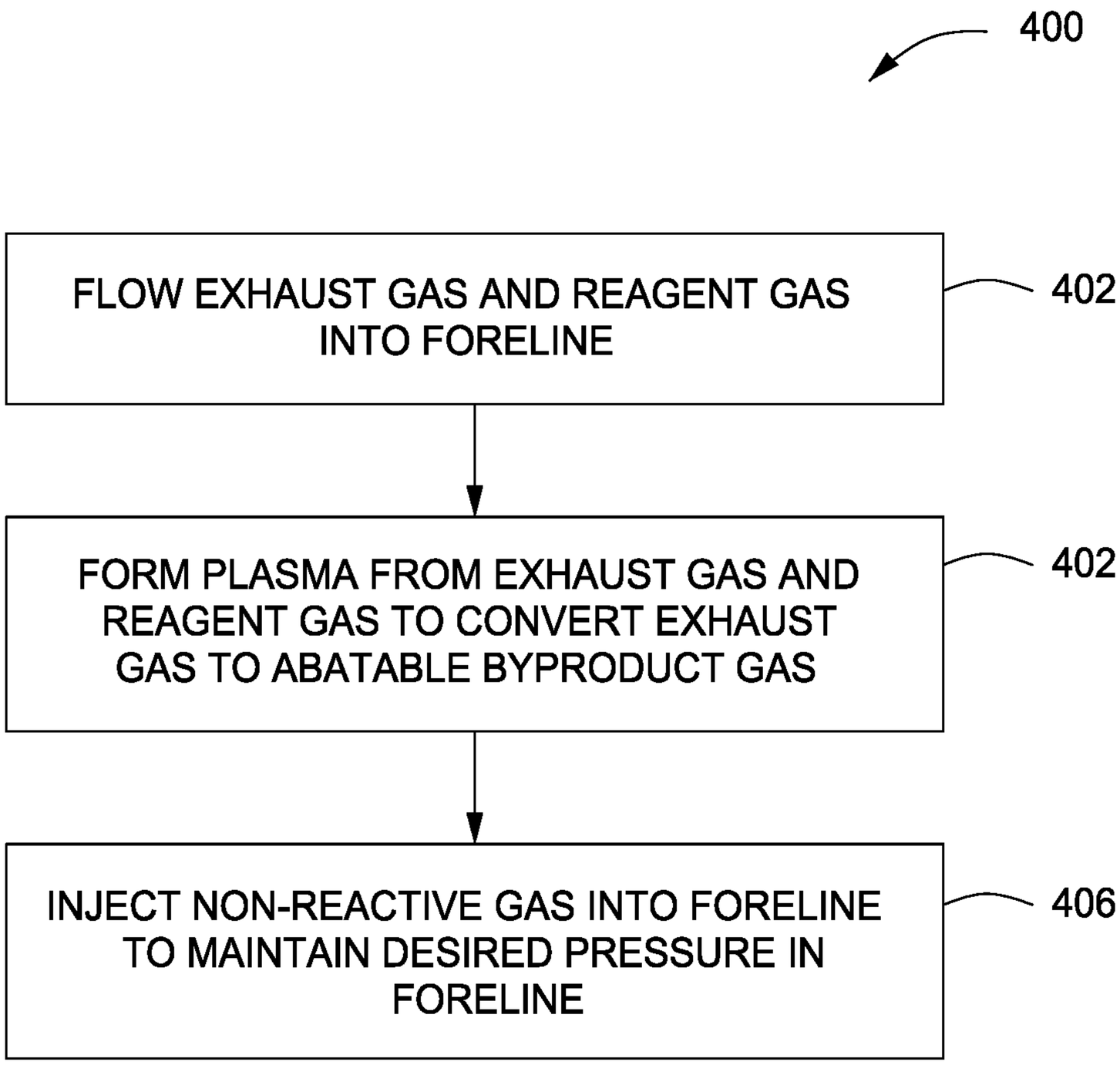

400
FLOW EXHAUST GAS AND REAGENT GAS INTO FORELINE
402
FORM PLASMA FROM EXHAUST GAS AND REAGENT GAS TO CONVERT EXHAUST GAS TO ABATABLE BYPRODUCT GAS
402
INJECT NON-REACTIVE GAS INTO FORELINE TO MAINTAIN DESIRED PRESSURE IN FORELINE
406

FIG. 4

# METHODS FOR TREATING EXHAUST GAS IN A PROCESSING SYSTEM

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application is continuation of co-pending U.S. patent application Ser. No. 15/449,226, filed Mar. 3, 2017, which is a divisional of U.S. patent application Ser. No. 14/300,372, filed Jun. 10, 2014 and issued as U.S. Pat. No. 9,597,634 on Mar. 21, 2017, which is a continuation of U.S. patent application Ser. No. 12/957,539, filed Dec. 1, 2010 and issued as U.S. Pat. No. 8,747,762 on Jun. 10, 2014, which claims benefit of U.S. provisional patent application Ser. No. 61/266,396, filed Dec. 3, 2009. Each of the aforementioned related patent applications is herein incorporated by reference in its entirety.

## FIELD

**[0002]** Embodiments of the present invention generally relate to the manufacture of electronic devices, and more specifically, to systems and methods for abating exhaust from electronic device manufacturing systems.

## BACKGROUND

**[0003]** Remote plasma sources (RPS) or in-line plasma sources (IPS) have been used for abatement of perfluorocarbons (PFC's) and global warming gases (GWG's). For example, the RPS or IPS may be installed in a foreline of a vacuum system of a substrate processing system between a high vacuum pump, such as a turbo pump, and a backing pump, such as a dry vacuum pump. However, there is currently no method or apparatus to control an operating pressure of the foreline (and hence the RPS or IPS) to optimize abatement of PFCs and/or GWGs. Accordingly, the inventors have provided improved methods and apparatus for treating exhaust gas in a processing system.

## SUMMARY

**[0004]** Methods and apparatus for treating an exhaust gas in a foreline of a substrate processing system are provided herein. In some embodiments, methods and apparatus may be provided to control foreline pressure to control and improve abatement destruction efficiency. In some embodiments, methods and apparatus may be provided to supply an intermittent or continuous cleaning gas flow to remove deleterious deposits that can accumulate on surfaces of a plasma abatement device coupled to the foreline. In some embodiments, the cleaning gas flow may be synchronized to the process for optimal cleaning and maximum substrate throughput.

**[0005]** In some embodiments, methods to selectively activate the pressure control or clean in sequence with the tool process recipe are provided to enhance the efficiency, throughput, and uptime of the system. In some embodiments, methods for cost effectively providing accurate and repeatable control of the reagent delivery rate are also provided. The combination of reagent injection control along with foreline pressure control may be provided to manage the plasma within an optimal operating range (for PFC or global warming gas abatement) in real-time.

**[0006]** In some embodiments, an apparatus for cleaning a foreline of a substrate processing system may include a plasma source coupled to a process foreline of a process chamber; a reagent source coupled to the process foreline upstream of the plasma source; and a foreline gas injection kit coupled to the process foreline to controllably deliver a gas to the process foreline, wherein the foreline injection kit includes: a pressure regulator to set a foreline gas delivery pressure setpoint; a gauge to monitor the foreline gas delivery pressure; and a fixed orifice to provide a known flow of gas at the pressure setpoint of the pressure regulator. In some embodiments, the foreline gas injection kit may further include an on/off control valve to selectively turn on and off the flow of the foreline gas to the process foreline. In some embodiments, the foreline gas injection kit may further include a pressure transducer to provide a signal corresponding to the pressure of the foreline gas; and a controller coupled to the signal from the pressure transducer to provide a feedback loop to control the pressure of the foreline gas.

**[0007]** In some embodiments, an apparatus for treating an exhaust gas in a foreline of a substrate processing system includes a plasma source coupled to a foreline of a process chamber, a reagent source coupled to the foreline upstream of the plasma source, and a foreline gas injection kit coupled to the foreline to controllably deliver a gas to the foreline, wherein the foreline injection kit includes a pressure regulator to set a foreline gas delivery pressure setpoint, and a first pressure gauge coupled to monitor a delivery pressure of the gas upstream of the foreline.

**[0008]** In some embodiments, a method for treating an exhaust gas in a foreline of a substrate processing system including flowing an exhaust gas and a reagent gas into a foreline of a substrate processing system, forming a plasma from the exhaust gas and reagent gas to convert the exhaust gas to abatable byproduct gases, and injecting a non-reactive gas into the foreline to maintain a desired pressure in the foreline for optimal conversion of the exhaust gas. Other and further embodiments of the present invention are described below.

**[0009]** Other and further embodiments of the present invention are described below.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** Embodiments of the present invention, briefly summarized above and discussed in greater detail below, can be understood by reference to the illustrative embodiments of the invention depicted in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

**[0011]** FIG. **1** depicts a substrate processing system in accordance with some embodiments of the present invention.

**[0012]** FIG. **2** depicts a substrate processing system in accordance with some embodiments of the present invention.

**[0013]** FIG. **3** depicts a substrate processing system in accordance with some embodiments of the present invention.

**[0014]** FIG. **4** depicts a flow chart of a method for treating an exhaust gas in accordance with some embodiments of the present invention.

**[0015]** To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. The

figures are not drawn to scale and may be simplified for clarity. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

## DETAILED DESCRIPTION

**[0016]** Methods and apparatus for treating an exhaust gas in a foreline of a substrate processing system are provided herein. Embodiments of the present invention may advantageously provide improved abatement efficiency for perfluorocarbons (PFC's) and global warming gases (GWG's). Embodiments of the present invention may improve abatement efficiency by, for example, controlling a pressure in the foreline to optimize breakdown of PFCs and/or GWGs by reaction with one or more reagent gases. For example, the pressure may be controlled in real-time to maintain the pressure within a desired operating range, or may be adjusted in response to one or more reagent gases injected into the foreline.

**[0017]** For example, in some embodiments, a plasma including a reagent (such as water) may be formed in or delivered to the process foreline while controlling the pressure in the process foreline to more optimally form and/or maintain the plasma. In some embodiments, methods to selectively activate the pressure control in sequence with the tool process recipe are provided to enhance the efficiency of the system. In some embodiments, methods for cost effectively providing accurate and repeatable control of the reagent delivery rate are also provided. The combination of reagent injection control along with foreline pressure control may be provided to manage the plasma within an optimal operating range (for PFC or GWG abatement) in real-time.

**[0018]** Embodiments of the present invention enable an in-line plasma abatement system (for example as schematically depicted in FIG. **1**) to maintain optimum abatement efficiency while minimizing use of foreline pressure control gases (such as $N_2$ or other gases discussed below), plasma reagents (such as water or other reagents discussed below), and electricity. The optimization can be optionally managed by real-time sensor feedback (examples include pressure, flow, and temperature), pre-determined operating conditions corresponding to each step in the recipe, or input from the process tool and gas control signals. The controlled, post-plasma foreline gas injection enables local line pressure control to optimize abatement performance. Alternatively, the foreline gas could be added pre-plasma (e.g., upstream of the RPS or IPS). However, a pre-plasma foreline gas addition would require considerably more plasma energy to fracture the foreline gas and the gases being abated (such as PFC's and GWG's) and could result in pressure cross-talk back to the process chamber.

**[0019]** Additional advantages of the post-plasma foreline gas injection include the reduction in temperature of the post abatement exhaust. As the pressure and gas flow in the exhaust line can change with each step in the recipe, this invention can adjust to each change in the recipe or for each operational condition to maintain optimum abatement efficiency while minimizing utilities and energy use for step. This control can be by set parameters time-synchronized to the process recipe, by real-time sensor feedback, or by monitoring the tool or gas panel control signals. If the abatement tool is in shutdown, idle, preventative maintenance, or bypass mode, energy and utilities can be minimized by use of the smart interface between the process chamber and the abatement device. For example, the smart interface may adjust the plasma power supply output to an appropriate power level to maintain target performance. The plasma power supply and reactor tube (or other component) lifetime depend on operating energy level. Wasting power by operating at a plasma energy level higher than is required for the abatement or clean gas within the reactor not only wastes energy, but shortens the duration between required maintenance. Further the abatement RPS or Inline Abatement Device smart interface may count and report: uptime, system warnings or faults, operating efficiency, operational hours, and utilities used, and may report real time or accumulative carbon footprint performance locally or to a central monitoring and reporting system. Further embodiments of this invention include a reagent delivery system designed and integrated with the foreline gas injection control to maintain a desired amount of reagent injected to the exhaust pre-plasma to maintain optimum abatement efficiency of PFC or GWG and to minimize reagent consumption.

**[0020]** A plasma source for foreline abatement may utilize a hydrogen or oxygen containing reagent, such as water vapor, in addition to the process exhaust, to enable PFC and GWG abatement in the foreline. FIG. **1** is a piping and instrumentation diagram that shows a typical plasma foreline abatement system in accordance with some embodiments of the invention. The plasma foreline abatement system may be coupled to or may be part of a larger processing system that produces or emits PFC's or GWG's that require abatement. Non-limiting examples of such systems include substrate processing systems such as those used in semiconductor, display, solar, or light emitting diode (LED) manufacturing processes.

**[0021]** For example, FIG. **1** depicts a schematic diagram of a substrate processing system **100** in accordance with some embodiments of the present invention. As shown in FIG. **1**, an exhaust conduit, or foreline **102** (for example, coupled to a process chamber or tool to carry exhaust from the chamber or tool, as indicated at **101**), may be provided with a plasma source **104** (such as a remote plasma source (RPS)) coupled in-line with the foreline **102**. The plasma source **104** may be implemented as a radical injector (e.g., an RPS) or as a process flow-through device (e.g., an IPS, where a plasma is created in the conduit through which the process exhaust flows). The plasma source **104** may be any plasma source coupled to the foreline **102** suitable for developing a plasma therein (such as a remote plasma source, an in-line plasma source, or the other suitable plasma source for generating a plasma—such as a capacitively coupled, inductively coupled, remote, or standing wave plasma—within the foreline or proximate the foreline and introduced into the foreline). The embodiments of FIGS. **1-3** are schematically represented and some components have been omitted for simplicity. For example, a high speed vacuum pump, such as a turbo pump or the like, may be disposed between the process chamber **101** and the foreline **102** for removing exhaust gases from the process chamber **101**.

**[0022]** A reagent delivery system **106** may be coupled to the foreline **102** to deliver a reagent, such as water vapor, to the foreline **102** upstream of the plasma source **104**. The reagent delivery system **106** may include a reagent source **105** (or multiple reagent sources (not shown)) coupled to the foreline **102** via one or more valves. For example, in some

embodiments, a valve scheme may include a control valve **103** which acts as an on/off switch for releasing reagent from the reagent source **105** and a flow control device **107** for controlling the flow rate of reagent into the foreline **102**. For example, as shown in FIG. **1**, the flow control device **107** can be disposed between the foreline **102** and the control valve **103**. The control valve **103** may be any suitable control valve such as a solenoid valve or the like. The flow control device **107** may be any suitable active or passive flow control device, for example, such as a fixed orifice, mass flow controller, needle valve or the like. In some embodiments, the reagent delivery system **106** may provide water vapor. In some embodiments, the reagent delivery system **106** may provide oxygen ($O_2$). However, use of $O_2$ as a reagent introduced into the foreline **102** may result in the formation of $OF_2$, which is very toxic. As such, $O_2$ may be used as a reagent primarily in regions where local regulations allow and/or where appropriate safety accommodations are in place.

**[0023]** Alternatively or in combination, reagents or additional reagents may be provided to the foreline **102** via a source coupled to the process chamber **101**, such as from a gas panel or the like. For example, in some embodiments, a gas panel and control system **111** coupled to the process chamber **101** can be used to supply a flow of a cleaning gas to the foreline **102** upstream of the plasma source **104**. The cleaning gas may facilitate removing deleterious deposits that can accumulate on surfaces of the plasma source **104**, such as a lumen of a reactor tube of the plasma source **104**.

**[0024]** The flow of the cleaning gas may be intermittent or continuous. The flow of the cleaning gas may be synchronized to the process for optimal cleaning and maximum substrate throughput. The cleaning gas may be most economically provided by the existing process gas panel and control system, which can supply any cleaning gas (such as, $NF_3$, $O_2$, Ar, $COF_2$, $H_2O$, $F_2$ or the like) either through the chamber (as shown) or optionally through a chamber bypass line (as shown by dashed line **113**) that provides the cleaning gas prior to, or upstream of, the plasma source **104**. In addition to providing optimal species to the plasma source **104** for cleaning, the intermittent or continuous addition of clean gas may be used to facilitate managing line pressure to provide optimal cleaning of deposits from the plasma abatement reactor tube. Although depicted only in FIG. **1**, the gas panel and control system **111** and the methods of use thereof may be incorporated in any of the embodiments disclosed herein.

**[0025]** A foreline gas injection kit **108** may be coupled to the foreline **102** upstream or downstream of the plasma source **104** (downstream depicted in FIG. **1**) to controllably provide a foreline gas, such as nitrogen ($N_2$), argon (Ar), or clean dry air (CDA), into the foreline **102** as desired to control the pressure within the foreline **102**. In some embodiments, the foreline gas being added may also control the exhaust gas temperature downstream of the device. Reducing the temperature of the foreline may significantly reduce failure of the foreline and other post abatement elastomeric or metal seals, and process pump components.

**[0026]** In some embodiments, such as shown in FIG. **1**, the foreline gas injection kit **108** may include a foreline gas source **109** followed by a pressure regulator **110** to set the gas delivery pressure setpoint, further followed by a control valve **112** to turn on and off the flow and finally a flow control device **114** such that a known flow of gas may be provided at the specific setpoint of the pressure regulator **110**. The control valve **112** may be any suitable control valve, such as discussed above for control valve **103**. The flow control device **114** may be any suitable flow control device, such as discussed above for flow control device **107**. In some embodiments, the flow control device **114** is a fixed orifice. In some embodiments the foreline gas injection kit **108** may further include a pressure gauge **116**, for example, disposed between the pressure regulator **110** and the flow control device **114**. For example, the pressure gauge **116** may be used to measure pressure in the kit **108** upstream of the flow control device **114**. For example, the measured pressure at the pressure gauge **116** may be utilized by a control device, such as a controller **118** discussed below, to set the pressure upstream of the flow control device **114** by controlling the pressure regulator **110**.

**[0027]** In some embodiments, the control valve **112** may be controlled by the system (e.g., controller **118**) to only turn gas on when the reagent from the reagent delivery system is flowing, such that usage of gas is minimized. For example, as illustrated by the dotted line between control valve **103** of the reagent delivery system **106** and the control valve **112** of the kit **108**, the control valve **112** may turn on (or off) in response to the control valve **103** being turned on (or off). In some embodiments, the reagent may flow only when the plasma abatement unit is turned on and commanded to abate the process. Alternative methods of control can be used other than the embodiment described above, such as a mass flow controller or a flow control needle valve instead of the fixed size orifice. In some embodiments a time delay or pre-activation of line pressure or reagent addition control may be employed for optimal performance results and plasma stability.

**[0028]** The foreline **102** may be coupled to a vacuum pump or other suitable pumping apparatus, as indicated at **120**, to pump the exhaust from the processing tool to appropriate downstream exhaust handling equipment (such as abatement equipment or the like). In some embodiments, the vacuum pump **120** may be a backing pump, such as a dry mechanical pump or the like. For example, the vacuum pump **120** may have a variable pumping capacity with can be set at a desired level, for example, to control or provided addition control of pressure in the foreline **102**.

**[0029]** The controller **118** may be coupled to the foreline abatement system for controlling the operation thereof. The controller **118** may be provided and coupled to various components of the substrate processing system **100** to control the operation thereof. For example, the controller may monitor and/or control the foreline gas injection kit **108**, the reagent delivery system **106**, and/or the plasma source **104** in accordance with the teachings disclosed herein. In some embodiments, the controller may be part of or coupled to a controller (not shown) of the process chamber **101** coupled to the foreline **102** to control the foreline abatement system in concert with the processing and recipes running in the process chamber.

**[0030]** The controller **118** may include a central processing unit (CPU), a memory, and support circuits. The controller **118** may control the substrate processing system **100** directly, or via computers (or controllers) associated with particular process chamber and/or support system components. The controller **118** may be one of any form of general-purpose computer processor that can be used in an industrial setting for controlling various chambers and sub-

processors. The memory, or computer readable medium, of the controller **118** may be one or more of readily available memory such as random access memory (RAM), read only memory (ROM), floppy disk, hard disk, optical storage media (e.g., compact disc or digital video disc), flash drive, or any other form of digital storage, local or remote. The support circuits are coupled to the CPU for supporting the processor in a conventional manner. These circuits include cache, power supplies, clock circuits, input/output circuitry and subsystems, and the like. Inventive methods as described herein may be stored in the memory as software routine that may be executed or invoked to control the operation of the substrate processing system **100** in the manner described herein. The software routine may also be stored and/or executed by a second CPU (not shown) that is remotely located from the hardware being controlled by the CPU of the controller **118**.

**[0031]** The configuration in FIG. **1** is exemplary and other variants of components may be provided to supply the foreline gas, the reagent, and/or the plasma. In addition, other components may be included in the substrate processing system **100** to provide enhanced functionality, efficiency, ease of use, or the like. For example, in some embodiments, and as shown in FIG. **2**, a vacuum valve **122** and a port **124**, such as an $N_2$ blanked port, may be coupled to the foreline **102** for temporary connection of a vacuum gauge for preliminary setup, testing, and the like. In some embodiments, the vacuum valve **122** and the port **124** may be coupled to the foreline **102** between the plasma source **104** and the foreline gas injection kit **108**.

**[0032]** In some embodiments, as shown in FIG. **3**, a pressure gauge **126**, such as a vacuum pressure transducer or the like, may be provided in the foreline **102** provide a pressure signal that may be used, for example, by the controller **118** in a feedback loop to control the regulating pressure of a pressure control valve **110** or the flow rate of the flow control device **114**, for example in embodiments where a mass flow controller is used, to enable dynamic control of the operating pressure of the plasma source **104**, e.g., the pressure in the foreline **102**. In some embodiments, for example when the vacuum pump **120** has variable pumping capacity, the controller may adjust the pumping capacity of the vacuum pump **120** in response to a foreline pressure measured by the pressure gauge **126**.

**[0033]** FIG. **4** depicts a flow chart for a method **400** for treating an exhaust gas in the foreline of a processing system. For example, the method **400** may be utilized with any of the embodiments of the substrate processing system **100** discussed herein. The exhaust gas may include a variety of exhaust gases resultant from performing a process in the process chamber **101**, such as unreacted process gases, byproduct gases formed from the interaction of one or more process gases and/or interaction of a process gas with a substrate, or the like. Exhaust gases that may benefit from the methods disclosed herein include, but are not limited to, PFCs and GWGs. The method **400** begins at **402** by flowing an exhaust gas and a reagent gas into a foreline, such as the foreline **102**, of a substrate processing system, such as the substrate processing system **100**. For example, the exhaust gas may have originated at the process chamber **101** and resulted from performing any of a number of processes, such as etching, deposition, cleaning, or the like. The reagent gas may be injected into the foreline **102**, for example, by the reagent delivery system **106**.

**[0034]** At **404**, a plasma may be formed form the exhaust gas and the reagent gas to convert the exhaust gas in abatable byproduct gases. For example, the abatement process can be illustrated by the following simple chemical formulas, for example, for $CF_4$ or $NF_3$ breakdown via plasma:

$$CF_4+2H_2O=CO_2+4HF$$

$$CF_4+H_2O=COF_2+2HF$$

$$4NF_3+6H_2O=2N_2+12HF+3O_2$$

**[0035]** The PFC or other global warming gas ($CF_4$ and $NF_3$ in the exemplary embodiments above), is reacted to break down the global warming gas and convert the fluorine to HF, which is easily scrubbed by traditional wet scrubbing technologies.

**[0036]** The ability of a remote plasma source or in-line plasma source to deliver energy to the plasma is dependent on matching of the power circuit of the remote plasma source to the operating process conditions. Hence, if the pressure in the vacuum foreline is too low, as a result of low process flow or large safety factor incorporated in the design of the vacuum system, it is not possible to deliver full power to the plasma and consequently the destruction efficiency for the PFC and GWG is undesirably reduced.

**[0037]** Accordingly, and at **406**, a non-reactive gas may be injected into the foreline **102** to maintain a desired pressure in the foreline for optimal conversion of the exhaust gas. For example, the non-reactive gas may be injected by the foreline gas injection kit **108**. In some embodiments, for example as illustrated in FIG. **1**, a first amount of the non-reactive gas may be injected in response to a second amount of the reagent gas flowed into the foreline **102**. For example, the controller may control the control valve **112** of the kit **108** to open or close in response to the opening or closing of the control valve **103** of the reagent delivery system **106**. Alternatively, the injection of the non-reactive gas may be response to a pressure level in the foreline **102**. For example, the pressure level in the foreline **102** as indicated by the pressure gauge **126** may be monitored by the controller **118**. The controller may adjust the flow rate of the non-reactive gas in the foreline **102** in response to the monitored pressure level. For example, the controller **118** may adjust one or more of the pressure regulator **110** or the flow control device **114** to maintain the desired pressure level in the foreline **102**.

**[0038]** In some embodiments, the method **400** may include flowing a cleaning gas into the foreline **102** to remove material deposited during conversion of the exhaust gas. For example, material may accumulate on one or more of surfaces of the foreline **102** or surfaces of the plasma source **104**. The flowing of the cleaning gas may occur, for example, between a desired number of process runs performed in the substrate processing system **100**. For example, a desired number of process runs may include between each substrate being processed, between a desired number of substrates being processed, or the like. Further, the cleaning gas may be provide by any of a number of sources, for example from the reagent delivery system **106**, or from the process chamber **101**, such as via a gas panel or the like.

**[0039]** In some embodiments, in operation, the foreline pressure and the stoichiometric ratio of water to a target species being abated with the plasma may be controlled, both separately and in concert with each other, for plasma abatement optimization. Embodiments of the present inven-

tion allow for tuning and setting fixed setpoints for these parameters. In some embodiments, the circuits may be tuned to control water ratio and local pressure via a pre defined recipe. In some embodiments, signals from the process controller may be used to set conditions, or signals from the chamber or process controller to the gas box may be used to control these setpoints. In some embodiments, in addition to controlling the foreline pressure and the stoichiometric ratio of water to a target species being abated with the plasma, the plasma power and RF match characteristics may also be tuned for different steps/parts of the process recipe. In addition to real time, by feedback sensor(s), or by recipe control of foreline pressure and control of stoichiometric ratio of water, in some embodiments the power output from the power supply may also be varied to add more power to the plasma for process steps that require greater power to achieve desired destruction removal efficiency and reduce the power consumption for steps that do not require as much power to achieve desired DRE.

**[0040]** For example, test results of processing in accordance with embodiments of the present invention show that the addition of a foreline gas injection kit to the system advantageously allows the pressure in the remote plasma source to be controlled for optimum power delivery to the plasma. Some embodiments of the invention may use a pressure regulator to set the nitrogen delivery pressure to a known setpoint, followed by a control valve to turn on and off the flow and finally an appropriately sized orifice such that a known flow of gas is provided at the specific set point of the pressure regulator. The nitrogen On/Off control valve may be controlled by the system to only turn gas on when water vapor is flowing such that usage of nitrogen is minimized. In some embodiments, the water vapor flow may flow only when the remote plasma abatement unit is turned on and commanded to abate the process. Alternative methods of nitrogen control can be used other than the embodiment described above, such as a mass flow controller or a flow control needle valve instead of the fixed size orifice. In some cases, for optimal operating conditions, a delayed or preemptive control signal may be used to start or stop reagent or foreline pressure flow control.

**[0041]** High abatement efficiency is also dependent on accurate setting of the water flow rate. The water delivery system includes a water tank that operates under vacuum conditions such that the water boils at low temperature from ambient to about 35 degrees Celsius. Control of the water vapor flow rate may be determined by the adjustment of the flow control device **107**. To enable accurate setting of this valve and repeatability of the setting, a micrometer needle valve has been incorporated so that the set point can be dialed in and specified precisely for a specific recipe, tool set, and/or operating condition. Once an application set point has been defined, future units manufactured for the application can be factory preset to the desired setting.

**[0042]** Although discussed above in context of an exhaust line abatement system, embodiments of the present invention may also apply to abatement, line cleaning, and chamber clean plasma applications.

**[0043]** Thus, methods and apparatus for treating an exhaust gas in a foreline of a substrate processing system have been provided herein. Embodiments of the present invention may advantageously provide improved abatement efficiency for perfluorocarbons (PFC's) and global warming gases (GWG's). Embodiments of the present invention may improve abatement efficiency by controlling a pressure in the foreline to optimize breakdown of PFCs and/or GWGs by reaction with one or more reagent gases. For example, the pressure may be controlled in real-time to maintain the pressure within a desired operating range, or may be adjusted in response to one or more reagent gases injected into the foreline.

**[0044]** While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof.

**1**. A method, comprising:
flowing an exhaust gas from a process chamber into a plasma source via a foreline,
injecting a reagent into the foreline;
forming a plasma in the plasma source from the exhaust gas and the reagent; and
injecting a cleaning gas into the foreline, wherein the cleaning gas and the reagent are different gases.

**2**. The method of claim **1**, wherein the reagent and the cleaning gas are injected into the foreline upstream of the plasma source.

**3**. The method of claim **1**, wherein the cleaning gas is injected into the plasma source intermittently.

**4**. The method of claim **1**, wherein the cleaning gas is injected into the plasma source continuously.

**5**. The method of claim **1**, wherein the reagent comprises water and the cleaning gas comprises oxygen gas.

**6**. A non-transitory computer readable medium having instructions stored thereon that, when executed, cause a method to be performed, the method comprising:
injecting a reagent into a foreline, the foreline configured to remove exhaust gas from a process chamber;
forming a plasma in a plasma source from the exhaust gas and the reagent; and
injecting a cleaning gas into the foreline, wherein the cleaning gas and the reagent are different gases.

**7**. The computer readable medium of claim **6**, wherein the reagent and the cleaning gas are injected into foreline upstream of the plasma source.

**8**. The computer readable medium of claim **6**, wherein the cleaning gas is injected into the plasma source intermittently.

**9**. The computer readable medium of claim **6**, wherein the cleaning gas is injected into the plasma source continuously.

**10**. The computer readable medium of claim **6**, wherein the reagent comprises water and the cleaning gas comprises oxygen gas.

**11**. A system, comprising:
a process chamber;
a foreline to flow an exhaust gas from the process chamber;
a plasma source coupled in-line with the foreline;
a reagent delivery system to inject a reagent into the foreline;
a gas panel to supply a flow of a cleaning gas to the foreline; and
a controller configured to:
inject the reagent into the foreline;
form a plasma in the plasma source from the exhaust gas and the reagent; and
inject the cleaning gas into the foreline, wherein the cleaning gas and the reagent are different gases.

**12**. The system of claim **11**, wherein the reagent and the cleaning gas are injected into the foreline upstream of the plasma source.

**13**. The system of claim **11**, wherein the cleaning gas is injected into the plasma source intermittently.

**14**. The system of claim **11**, wherein the cleaning gas is injected into the plasma source continuously.

**15**. The system of claim **11**, wherein the reagent comprises water and the cleaning gas comprises oxygen gas.

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