

LEVEL MONITORING OF SOLID PRECURSORS

INCORPORATION BY REFERENCE

[0001] A PCT Request Form is filed concurrently with this specification as part of the present application. Each application that the present application claims benefit of or priority to as identified in the concurrently filed PCT Request Form is incorporated by reference herein in its entirety and for all purposes.

BACKGROUND

[0002] Semiconductor manufacturing typically involves one or more processes to deposit and pattern a structure on a wafer. For example, in some semiconductor manufacturing processes a film is created on a semiconductor wafer by flowing a vaporized precursor onto the wafer and then activating a reaction on the substrate surface. The precursor material may be containerized as a solid in an ampoule that is configured to deliver to the wafer, as needed, vapor sublimated from the solid. Thus, the solid precursor is consumed during operation, and the ampoule may need to be periodically refilled or replaced with a replacement ampoule containing a fresh supply of precursor material.

[0003] The background description provided herein is for the purposes 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.

SUMMARY

[0004] Techniques for monitoring a fill level of solid precursors disposed in an ampoule of a substrate processing apparatus, where the ampoule is fluidically coupled with a processing chamber and the substrate processing apparatus is configured to cause at least a portion of the solid precursor to sublime, and to deliver resulting gaseous precursor chemicals to the processing chamber are disclosed.

[0005] According to some embodiments, a method includes monitoring, with a controller communicatively coupled with at least one sensor, data from the sensor relating to the fill level of a solid precursor, determining whether the monitored data meets a criterion for replacing the ampoule, and, in response to determining that the monitored data meets the criterion, initiating

a process to refill or replace the ampoule.

[0006] In some examples, determining whether the monitored data meets the criterion may include determining that a remaining volume of the solid precursor is below a threshold volume.

[0007] In some examples, initiating the process may include at least one of alerting an operator and commencing a soft shutdown. In some examples, the at least one sensor includes a proximity detector disposed above the solid precursor. In some examples, the proximity detector may be configured to detect a distance between the proximity detector and a top surface of the solid precursor. In some examples, the proximity sensor may be at least one of a photoelectric, capacitive, and inductive sensor. In some examples, the proximity sensor may be an ultrasonic time-of-flight measurement device optical capacitive or an optical distance sensor. In some examples, the method may include heating the proximity sensor to a temperature above a sublimation temperature of the solid precursor. In some examples, the proximity sensor may be disposed on or through a top surface of the ampoule or an upper surface of a wall of the ampoule. In some examples, the at least one sensor may be a proximity detector disposed in a lower portion of the solid precursor. In some examples, the proximity detector may include an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor. In some examples, the at least one sensor may be disposed within a lower wall of the ampoule. In some examples, the at least one sensor may include an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor. In some examples, the at least one sensor may be an acoustic measuring device. In some examples, the acoustic measuring device may include a mechanical transmitter and an acoustic receiver. In some examples, the mechanical transmitter may be configured to strike an external surface of a wall of the ampoule and the acoustic receiver may be configured to receive acoustic signals resulting from the strike and convert the signals into electrical signals. In some examples, the monitored data includes the electrical signals.

[0008] According to some embodiments, a system includes: an ampoule of a substrate processing apparatus, where the ampoule is fluidically coupled with a processing chamber and the substrate processing apparatus is configured to cause at least a portion of a solid precursor disposed in the ampoule to sublime, and to deliver resulting gaseous precursor chemicals to the processing chamber; at least one sensor; and one or more controllers configured to: monitor data from the sensor relating to a fill level of the solid precursor; determine whether the

monitored data meets a criterion for replacing the ampoule; and, in response to determining that the monitored data meets the criterion, initiate a process to refill or replace the ampoule.

[0009] In some examples, the one or more controllers may be configured to determine whether the monitored data meets the criterion by determining that a remaining volume of the solid precursor is below a threshold volume.

[0010] In some examples, the one or more controllers may be configured to initiate the process by at least one of alerting an operator and commencing a soft shutdown. In some examples, the at least one sensor may include a proximity detector disposed above the top surface of the solid precursor. In some examples, the proximity detector may be configured to detect a distance between the proximity detector and a top surface of the solid precursor. In some examples, the proximity sensor may be at least one of a photoelectric, capacitive, and inductive sensor. In some examples, the proximity sensor may be an ultrasonic time-of-flight measurement device optical capacitive or an optical distance sensor. In some examples, the system may include a heater configured to heat the proximity sensor to a temperature above a sublimation temperature of the solid precursor. In some examples, the proximity sensor may be disposed on or through a top surface of the ampoule or an upper surface of a wall of the ampoule. In some examples, the at least one sensor may be a proximity detector disposed in a lower portion of the solid precursor. In some examples, the proximity detector may include an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor. In some examples, the at least one sensor may be disposed within a lower wall of the ampoule. In some examples, the at least one sensor may include an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor. In some examples, the at least one sensor may be an acoustic measuring device. In some examples, the acoustic measuring device may include a mechanical transmitter and an acoustic receiver. In some examples, the mechanical transmitter may be configured to strike an external surface of a wall of the ampoule and the acoustic receiver may be configured to receive acoustic signals resulting from the strike and convert the signals into electrical signals. In some examples, the monitored data may include the electrical signals.

[0011] These and other features of the disclosed embodiments will be described in detail below with reference to the associated drawings.

BRIEF DESCRIPTION OF DRAWINGS

[0012] Fig. 1 shows a simplified schematic example of an apparatus for a substrate processing system with an ampoule containing a solid precursor.

[0013] Fig. 2 shows an example implementation, in which a proximity detector is disposed above the solid precursor.

[0014] Fig. 3 shows an example implementation, in which a proximity detector is disposed in a lower portion of the solid precursor.

[0015] Fig. 4 shows an example implementation, in which a proximity detector is disposed within a lower wall of the ampoule.

[0016] Fig. 5 shows an example implementation, in which a fill sensor is disposed externally of and proximate to the ampoule.

[0017] Fig. 6 shows an example system block diagram, according to some implementations.

[0018] Fig. 7 shows a process flow diagram, according to some implementations.

DETAILED DESCRIPTION

[0019] In the following description, numerous specific details are set forth to provide a thorough understanding of the presented embodiments. The disclosed embodiments may be practiced without some or all of these specific details. In other instances, well-known process operations have not been described in detail to not unnecessarily obscure the disclosed embodiments. While the disclosed embodiments will be described in conjunction with the specific embodiments, it will be understood that it is not intended to limit the disclosed embodiments.

[0020] The subscripts “x” and “y” are used throughout the disclosure to denote a number greater than zero that forms a stable compound. However, it should be noted that the lack of an “x” or other subscript (e.g., in titanium nitride (TiN) or titanium oxynitride (TiON)) does not imply a particular atomic ratio.

[0021] Described herein are techniques for monitoring the level of a solid precursor in an ampoule configured to store the solid precursor and to sublime and deliver a gas including gaseous sublimated precursor chemicals to a processing chamber.

[0022] Figure 1 shows a simplified schematic example of an apparatus for a substrate processing system including a precursor ampoule of a type contemplated by the present disclosure. In the illustrated example, an apparatus 100 includes an ampoule 102 fluidically coupled with a processing chamber (not illustrated).

[0023] In the illustrated example, the ampoule 102 is configured to store a supply of solid

precursor 104. A solid precursor may be desirable for certain applications. For example, conductive lines in semiconductor memory devices increasingly use molybdenum and precursors for molybdenum deposition may preferably be containerized within the ampoule 102 in a solid state. Examples include molybdenum chloride (MoCl_x), molybdenum oxychloride, and certain molybdenum organometallic compounds. Molybdenum chloride precursors are given by the formula MoCl_x , where x is 2, 3, 4, 5, or 6, and include molybdenum dichloride (MoCl_2), molybdenum trichloride (MoCl_3), molybdenum tetrachloride (MoCl_4), molybdenum pentachloride (MoCl_5), and molybdenum hexachloride (MoCl_6). In some embodiments, MoCl_5 or MoCl_6 are used.

[0024] In some implementations, the ampoule 102 may have a volume of between about 500 mL to 5 L. The ampoule 102 may have a precursor capacity of approximately 5-10 kgs, in some implementations. The ampoule 102 may typically be pre-loaded with the solid precursor 104, which is consumed over time, as a result of the solid precursor 104 being sublimated and the resulting gaseous precursor chemicals in region 103 being delivered to the processing chamber. Before the ampoule 102 is totally depleted of solid precursor, it may be replaced with a new pre-loaded ampoule 102, or refilled, an operation that may typically be necessary every 1-12 months.

[0025] Flow path 106 connects the substrate processing apparatus 100 with a source of carrier gas. In some implementations, the carrier gas may be argon, for example. The flow of the carrier gas through the flow path 106 into the rest of the flow paths of the substrate processing apparatus 100 may be controlled by a valve 108. If the valve 108 is closed, there may be no fluid flow through the substrate processing apparatus 100.

[0026] In the illustrated implementation, flow path 134 connects the flow path 106 with the ampoule 102 and a valve 110 located on flow path 134 controls the flow of carrier gas from the flow path 106 into the ampoule 102. After the carrier gas flows into region 103 of the ampoule 102, it may mix with gaseous precursor chemicals sublimated from the solid precursor 104.

[0027] In the illustrated implementation, flow paths 118 and 136 provide fluidic coupling between the ampoule 102 and the processing chamber and a valve 116 located on flow path 136 may be configured to control the flow of gaseous precursor chemicals from the region 103 of the ampoule 102 to the processing chamber. Additionally, in the illustrated implementation, a valve 124 is also located on flow path 118 and may be configured to control the flow of carrier gas to the processing chamber.

[0028] As noted hereinabove, the solid precursor 104 may be consumed over a period of time

during operation of processing apparatus 100, with the ampoule 102 eventually becoming depleted of the solid precursor 104. If the ampoule 102 becomes depleted of the solid precursor 104 during semiconductor processing, it may result in a costly unanticipated shutdown of one or several processing chambers, and damage to or complete loss of valuable in-process semiconductor work pieces. On the other hand, replacing a used ampoule 102 with a new ampoule 102 (e.g., one fully loaded with the solid precursor 104), or refilling the ampoule 102 earlier than necessary may be wasteful of material and processing time.

[0029] Thus, it is desirable to know the level of the solid precursor 104 remaining in the ampoule 102 during operation, so that necessary replacement of the ampoule 102 can be timely performed (i.e., before, but not excessively before, the ampoule 102 becomes depleted). Direct measurement of the level of the solid precursor 104 remaining in the ampoule 102 may be difficult, however, because the solid precursor 104 may have various morphologies (e.g., a single crystalline solid, a powder, or granularized particles of various sizes, for example). Moreover, sensors may be incompatible with an ampoule's operating conditions (e.g., temperatures in the range of 80-150°C and exposure to gaseous precursor chemicals at those temperatures).

[0030] In some implementations, techniques for monitoring a fill level of a solid precursor disposed in an ampoule of a processing apparatus are contemplated, the ampoule being fluidically coupled with a substrate processing chamber. As described hereinbelow, at least one sensor may be associated with the ampoule and be configured to, for example, include a device disposed interior or exterior to the ampoule, embedded in an ampoule wall or protruding through an ampoule wall such that a portion of the device is within the ampoule and a portion is outside the ampoule. In some implementations, capacitive, inductive, radar, optical, ultrasonic, or acoustic sensors may be contemplated. Data from the sensor relating to the fill level of the solid precursor may be monitored by a controller communicatively coupled with the sensor and may be configured to determine whether the monitored fill level meets a criterion for replacing or refilling the ampoule. The criterion may be, for example, that a distance between a top of the ampoule and a top of the solid precursor is less than a specified distance, or that a distance between a bottom of the ampoule and the top of the solid precursor is greater than a specified distance. In response to determining that the monitored fill level meets the criterion, a process to refill or replace the ampoule may be initiated. In some implementations, determining whether the monitored fill level meets the criterion may include determining that a remaining volume of the solid precursor is below a threshold volume. The threshold volume may correspond to an amount of solid precursor sufficient for a specified

amount of normal operation (e.g., 10-24 hours, 1-7 days).

[0031] In some implementations, the process to refill or replace the ampoule may include at least one of alerting an operator and commencing a “soft shutdown” of at least one of the substrate processing apparatus and the processing chamber. A soft shutdown may include, for example, stopping further deposition steps or other procedures typically undertaken during normal processing. In some implementations, a soft shutdown may include finishing a wafer currently being processing in the chamber, removal of other wafers. In certain embodiments, the soft shutdown process may generate a notification to an operator or process controller.

[0032] In some implementations, the at least one sensor may include a proximity detector configured to detect a distance between the proximity detector and a top surface of the solid precursor. Fig. 2 shows an example implementation, in which proximity detector 240 is disposed above the solid precursor 104 and is configured to detect a distance ‘ d_I ’ between a lower surface of a sensing head 242 of the proximity detector 240 and a top surface of the solid precursor 104. The proximity sensor may be a photoelectric, capacitive, and/or inductive sensor, for example, where the sensor head 242 is configured to withstand the operating conditions of region 103 within ampoule 102. A body 241 of the proximity detector 240 may be disposed exterior to the ampoule 102, and be attached thereto by a mechanical means 243, for example a nut. Commercially available high temperature proximity sensors suitable for such implementations are available from Locon Sensor Systems, Inc., for example. The proximity detector 240 may be communicatively coupled or wirelessly coupled with a controller (not illustrated) or by way of electrical cabling (not illustrated) coupled with the body 241. The controller may be configured to use data received from the proximity sensor 240 to determine whether the monitored fill level meets a criterion for replacing or refilling the ampoule 102.

[0033] In some implementations, the proximity detector 240 may include an ultrasonic time-of-flight measurement device. Such a device may, for example, emit ultrasonic pulses that are reflected back, as an ultrasonic echo, towards the device from an object of interest (in the present example, the top surface of the solid precursor 104. By monitoring the separation in time between emitting the ultrasonic pulse and receiving the ultrasonic echo, the distance ‘ d_I ’ may be determined. Suitable devices for such implementations are available from Endress+Hauser Group Services AG, for example. In some implementations, the proximity detector 240 may include a non-contact radar level meter. Suitable devices for such implementations are available from Supmea Automation Co. Ltd., for example. In some implementations, the proximity detector 240 may include an optical distance sensor such as a

diffuse photoelectric sensor, for example. Suitable devices for such implementations are available from Proxitron GmbH, for example. The proximity detector 240, in any case, may be communicatively coupled or wirelessly coupled with a controller (not illustrated) or by way of electrical cabling (not illustrated) coupled with the body 241. The controller may be configured to use data received from the proximity sensor 240 to determine whether the monitored fill level meets a criterion for replacing or refilling the ampoule 102.

[0034] Referring still to Fig. 2, in any of the above described implementations, it may be desirable to equip the proximity detector 240 with a heating device wherewith the sensing head 242 may be maintained at a temperature above the sublimation temperature of the solid precursor 104. This may be advantage to prevent condensation of gaseous precursor materials onto the sensing head 242.

[0035] Fig. 3 shows an example implementation, in which a proximity detector 340 is disposed in a lower portion of the solid precursor 104. In the illustrated example, the proximity detector 340 is disposed on an interior surface of bottom wall of ampoule 102. The proximity detector 340 may be configured to detect a distance ' d_2 ' between an upper surface of the proximity detector 340 and a top surface of the solid precursor 104. The proximity detector 340 may include an ultrasonic time-of-flight measurement device such as described above in connection with Fig. 2. The proximity detector 340 may be communicatively coupled with a controller (not illustrated) wirelessly or by way of electrical cabling (not illustrated). The controller may be configured to use data received from the proximity sensor 340 to determine whether the monitored fill level meets a criterion for replacing or refilling the ampoule 102.

[0036] Fig. 4 shows an example implementation, in which a proximity detector 440 is disposed within a lower wall of ampoule 102. In the illustrated example, the proximity detector 440 is disposed within a bottom wall of ampoule 102. The proximity detector 440 may be configured to detect a distance ' d_3 ' between an upper surface of the proximity detector 440 and a top surface of the solid precursor 104. The proximity detector 440 may include an ultrasonic time-of-flight measurement device such as described above in connection with Fig. 2 and Fig. 3. The proximity detector 440 may be communicatively coupled with a controller (not illustrated) wirelessly or by way of electrical cabling (not illustrated). The controller may be configured to use data received from the proximity sensor 440 to determine whether the monitored fill level meets a criterion for replacing or refilling the ampoule 102.

[0037] Fig. 5 shows an example implementation, in which a fill sensor 540 is disposed externally of and proximate to ampoule 102. The fill sensor 540 may be an acoustic measuring device including a mechanical transmitter 544 and an acoustic receiver 545. The mechanical

transmitter 544 may be configured to tap or strike an external surface of a wall of ampoule 102. For example, the mechanical transmitter may include an actuator that strikes, or propels an impactor mass to strike the external wall surface. The acoustic receiver 545 may be a microphone, for example, and may be configured to receive acoustic signals resulting from the strike and convert the signals into electrical signals. As the fill level of the solid precursor 104 within the ampoule 102 changes, characteristics of the acoustic signals may be expected to change. A correlation between the resulting signals and the fill level of the solid precursor 104 may be obtained, experimentally, for example, for any particular ampoule configuration and type of solid precursor 104. The acoustic receiver 545 may be communicatively coupled with a controller (not illustrated) wirelessly or by way of electrical cabling (not illustrated). The controller may be configured, based on the obtained correlation, to associate certain signals from the acoustic receiver 545 with a fill level meeting a criterion for replacing or refilling the ampoule 102.

[0038] Fig. 6 illustrates a simplified block diagram of an example of a system in accordance with some implementations. In the illustrated example, a system 600 includes an ampoule 602 of a substrate processing apparatus. The ampoule 602 may be fluidically coupled with a processing chamber (not illustrated). A solid precursor disposed in the ampoule 602 may be caused to sublime, and the ampoule 602 may deliver resulting gaseous precursor chemicals to the processing chamber. At least one sensor 640 is associated with the ampoule 602 and may be configured to acquire data relating to a fill level of the solid precursor in the ampoule 602. One or more controllers 650 are configured to monitor the data from the sensor relating to a fill level of the solid precursor, determine whether the monitored data meets a criterion for replacing the ampoule 602; and, in response to determining that the monitored fill level meets the criterion initiate a process to refill or replace the ampoule 602.

[0039] The one or more controllers 650 may be configured to determine whether the monitored fill level meets the criterion by determining that a remaining volume of the solid precursor is below a threshold volume. The one or more controllers 650 may be configured to initiate the process by alerting an operator and/or commencing a soft shutdown. It will be appreciated that the one or more controllers 650 may additionally be configured to control, referring to Fig. 1, for example, valves 108, 110, 116 and 124 and/or to interface with other actuators and sensors associated with the substrate processing system with which the apparatus 100 is associated.

[0040] The one or more controllers 650 will typically include one or more memory devices and one or more processors. A processor may include a CPU or computer, analog and/or digital input/output connections, stepper motor controller boards, etc.

[0041] There may be a user interface associated with the one or more controllers 650. The user interface may include a display screen, graphical software displays of the apparatus and/or process conditions, and user input devices such as pointing devices, keyboards, touch screens, microphones, etc.

[0042] System control logic may be configured in any suitable way. In general, the logic can be designed or configured in hardware and/or software. The instructions for controlling the drive circuitry may be hard coded or provided as software. The instructions may be provided by “programming.” Such programming is understood to include logic of any form, including hard coded logic in digital signal processors, application-specific integrated circuits, and other devices which have specific algorithms implemented as hardware. Programming is also understood to include software or firmware instructions that may be executed on a general-purpose processor. System control software may be coded in any suitable computer readable programming language.

[0043] The computer program code may be written in any conventional computer readable programming language: for example, assembly language, C, C++, Pascal, Fortran, or others. Compiled object code or script is executed by the processor to perform the tasks identified in the program. Also as indicated, the program code may be hard coded.

[0044] Signals for monitoring the process may be provided by analog and/or digital input connections of the one or more controllers 650.

[0045] Broadly speaking, the one or more controllers 650 may be defined as electronics having various integrated circuits, logic, memory, and/or software that receive instructions, issue instructions, and control operations. 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). 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.

[0046] The one or more controllers 650, in some implementations, may be a part of or coupled to a computer that is integrated with, coupled to the system, otherwise networked to the system, or a combination thereof. For example, the one or more controllers 650 may be in the “cloud” or all or a part of a fabrication 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. 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. 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. Thus, as described above, the controller may be distributed, such as by including 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.

[0047] Referring now to Fig. 7, a method 700 for monitoring a fill level of a solid precursor disposed in an ampoule of a substrate processing apparatus will be described. As indicated above, the ampoule may be fluidically coupled with a processing chamber and the substrate processing apparatus may be configured to cause at least a portion of the solid precursor to sublime, and to deliver resulting gaseous precursor chemicals to the processing chamber.

[0048] At block 760, in the illustrated example, data from a sensor relating to the fill level of the solid precursor is monitored.

[0049] At block 770, it is determined whether the monitored data meets a criterion for replacing the ampoule. If the criterion is not met, the method may continue to monitor the sensor data (block 760), either immediately, or after an interval (e.g., after a certain number of hours of consumption of the solid precursor). If the criterion is met, the method may conclude, at block 780, with initiating a process to refill or replace the ampoule. In some implementations, initiating the process to refill or replace the ampoule includes at least one of alerting an operator and commencing a soft shutdown.

Conclusion

[0050] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. Embodiments disclosed herein may be

practiced without some or all of these specific details. In other instances, well-known process operations have not been described in detail to not unnecessarily obscure the disclosed embodiments. Further, while the disclosed embodiments will be described in conjunction with specific embodiments, it will be understood that the specific embodiments are not intended to limit the disclosed embodiments. It should be noted that there are many alternative ways of implementing the processes, systems, and apparatus of the present embodiments. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the embodiments are not to be limited to the details given herein.

CLAIMS

What is claimed is:

1. A method comprising:
monitoring, with a controller communicatively coupled with at least one sensor, data from the sensor relating to a fill level of a solid precursor disposed in an ampoule of a substrate processing apparatus, wherein the ampoule is fluidically coupled with a processing chamber and the substrate processing apparatus is configured to cause at least a portion of the solid precursor to sublime, and to deliver resulting gaseous precursor chemicals to the processing chamber;
determining whether the monitored data meets a criterion for replacing the ampoule;
and,
in response to determining that the monitored data meets the criterion, initiating a process to refill or replace the ampoule.
2. The method of claim 1, wherein determining whether the monitored data meets the criterion includes determining that a remaining volume of the solid precursor is below a threshold volume.
3. The method of claim 1, wherein initiating the process includes at least one of alerting an operator and commencing a soft shutdown.
4. The method of claim 3, wherein the at least one sensor comprises a proximity detector disposed above the solid precursor.
5. The method of claim 4, wherein the proximity detector is configured to detect a distance between the proximity detector and a top surface of the solid precursor.
6. The method of claim 4, wherein the proximity sensor is at least one of a photoelectric, capacitive, and inductive sensor.
7. The method of claim 4, wherein the proximity sensor is an ultrasonic time-of-flight measurement device optical capacitive or an optical distance sensor.

8. The method of claim 4, further comprising heating the proximity sensor to a temperature above a sublimation temperature of the solid precursor.

9. The method of claim 4, wherein the proximity sensor is disposed on or through a top surface of the ampoule or an upper surface of a wall of the ampoule.

10. The method of claim 3, wherein the at least one sensor is a proximity detector disposed in a lower portion of the solid precursor.

11. The method of claim 10, wherein the proximity detector comprises an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor.

12. The method of claim 3, wherein the at least one sensor is disposed within a lower wall of the ampoule.

13. The method of claim 12, wherein the at least one sensor comprises an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor.

14. The method of claim 3, wherein the at least one sensor is an acoustic measuring device.

15. The method of claim 14, wherein the acoustic measuring device comprises a mechanical transmitter and an acoustic receiver.

16. The method of claim 15, wherein the mechanical transmitter is configured to strike an external surface of a wall of the ampoule and the acoustic receiver is configured to receive acoustic signals resulting from the strike and convert the signals into electrical signals.

17. The method of claim 16, wherein the monitored data includes the electrical signals.

18. A system comprising:
an ampoule of a substrate processing apparatus, wherein the ampoule is configured to contain a solid precursor and is fluidically coupled with a processing chamber and the substrate processing apparatus is configured to cause at least a portion of the solid precursor to sublime, and to deliver resulting gaseous precursor chemicals to the processing chamber;
at least one sensor
and one or more controllers configured to:
monitor data from the sensor relating to a fill level of the solid precursor;
determine whether the monitored data meets a criterion for replacing the ampoule; and,
in response to determining that the monitored data meets the criterion, initiate a process to refill or replace the ampoule.
19. The system of claim 18, wherein the one or more controllers are configured to determine whether the monitored data meets the criterion by determining that a remaining volume of the solid precursor is below a threshold volume.
20. The system of claim 18, wherein the one or more controllers are configured to initiate the process by at least one of alerting an operator and commencing a soft shutdown.
21. The system of claim 20, wherein the at least one sensor comprises a proximity detector disposed above the top surface of the solid precursor.
22. The system of claim 21, wherein the proximity detector is configured to detect a distance between the proximity detector and a top surface of the solid precursor.
23. The system of claim 21, wherein the proximity sensor is at least one of a photoelectric, capacitive, and inductive sensor.
24. The system of claim 21, wherein the proximity sensor is an ultrasonic time-of-flight measurement device optical capacitive or an optical distance sensor.
25. The system of claim 21, further comprising a heater configured to heat the proximity sensor to a temperature above a sublimation temperature of the solid precursor.

26. The system of claim 21, wherein the proximity sensor is disposed on or through a top surface of the ampoule or an upper surface of a wall of the ampoule.

27. The system of claim 20, wherein the at least one sensor is a proximity detector disposed in a lower portion of the solid precursor.

28. The system of claim 27, wherein the proximity detector comprises an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor.

29. The system of claim 20, wherein the at least one sensor is disposed within a lower wall of the ampoule.

30. The system of claim 29, wherein the at least one sensor comprises an ultrasonic time-of-flight measurement device configured to detect a distance between the ultrasonic time-of-flight measurement device and a top surface of the solid precursor.

31. The system of claim 20, wherein the at least one sensor is an acoustic measuring device.

32. The system of claim 31, wherein the acoustic measuring device comprises a mechanical transmitter and an acoustic receiver.

33. The system of claim 32, wherein the mechanical transmitter is configured to strike an external surface of a wall of the ampoule and the acoustic receiver may be configured to receive acoustic signals resulting from the strike and convert the signals into electrical signals.

34. The system of claim 33, wherein the monitored data includes the electrical signals.