processing chamber 10, and the substrate support 11. The plasma processing chamber 10 has at least one gas inlet for supplying at least one process gas into the plasma processing space 10s and at least one gas outlet for discharging the gas from the plasma processing space. The plasma processing chamber 10 is grounded. The shower head 13 and the substrate support 11 are electrically insulated from a housing of the plasma processing chamber 10.

[0032] The substrate support 11 includes a body 111 and a ring assembly 112. The body 111 includes a central area 111a for supporting a substrate W and an annular area 111b for supporting the ring assembly 112. A wafer is an example of the substrate W. The annular area 111b of the body 111 surrounds the central area 111a of the body 111 as viewed in plan. The substrate W is located on the central area 111a of the body 111. The ring assembly 112 is located on the annular area 111b of the body 111 to surround the substrate W on the central area 111a of the body 111. Thus, the central area 111a is also referred to as a substrate support surface for supporting the substrate W, and the annular area 111b is also referred to as a ring support surface for supporting the ring assembly 112.

[0033] In one embodiment, the body 111 includes a base 1110 and an electrostatic chuck (ESC) 1111. The base 1110 includes a conductive member. The conductive member in the base 1110 may serve as a lower electrode. The ESC 1111 is located on the base 1110. The ESC 1111 includes a ceramic member 1111a and an electrostatic electrode 1111b located inside the ceramic member 1111a. The ceramic member 1111a includes the central area 111a. In one embodiment, the ceramic member 1111a also includes the annular area 111b. Other members surrounding the ESC 1111, such as an annular ESC or an annular insulating member, may include the annular area 111b. In this case, the ring assembly 112 may be located on the annular ESC or the annular insulating member, or may be located on both the ESC 1111 and the annular insulating member. A radio-frequency (RF) electrode or a direct-current (DC) electrode may also be located inside the ceramic member 1111a. In this case, the RF electrode or the DC electrode serves as a lower electrode. When a bias RF signal or a DC signal (described later) is provided to the RF electrode or the DC electrode, the RF electrode or the DC electrode is also referred to as a bias electrode. The conductive member in the base 1110 and the RF electrode or the DC electrode may serve as two lower electrodes.

Other Examples of Step ST2

[0090] FIG. 7 is another example timing chart for step ST2 using a reaction accelerator gas. FIG. 7 shows an example of etching of the silicon-containing film SF in repeated multiple cycles of step ST21 of the first etching and step ST2 of the second etching using a reaction accelerator gas as the reaction control gas. The vertical axis and the horizontal axis in FIG. 7 are the same as the axes in FIG. 4, with $P_B$ indicating, for the reaction accelerator gas, a partial pressure of zero or a partial pressure lower than a partial pressure indicated by $P_A$. In the figure, $L_B$ indicates the adsorption level (adsorption amount) of hydrogen fluoride to the silicon-containing film SF less than that of $L_A$. In FIG. 7, for example, times 0 to t21 and times t22 to t23 correspond to step ST21 (these periods are hereinafter referred to as the period H1, the period H2, or other periods). For example, times t21 to t22 and times t23 to t24 correspond to step ST22 (these periods are hereinafter referred to as the period L1, the period L2, or other periods).

[0091] In FIG. 7, the partial pressure of the reaction accelerator gas is constant in each period (the period H1, period H2, period L1, and period L2), but may vary (decrease, increase, or increase and decrease) in a stepwise manner or sequentially within each period. In this case, the adsorption level of hydrogen fluoride can change to follow the variation.

[0092] FIG. 7 is a timing chart for step ST2 using a reaction accelerator gas as the reaction control gas. Instead of or in addition to this, a reaction inhibitor gas may be used as the reaction control gas. FIG. 8 is another example timing chart for step ST2 using a reaction inhibitor gas. As shown in FIG. 8, the partial pressure of the reaction inhibitor gas may be low or zero ($P_D$) in step ST1 (the period H1 and period H2) and high ($P_C$) in step ST2 (the period L1 and period L2). The adsorption level ($L_C$) of hydrogen fluoride in step ST1 (the period H1 and period H2) is higher than the adsorption level ($L_D$) of hydrogen fluoride in step ST2 (the period L1 and period L2).

[0093] FIG. 9A is a diagram of the substrate W showing an example cross-sectional structure at the end of the period H1 (step ST21 of the first cycle) (time t21) in FIG. 7 or FIG. 8. FIG. 9B is a diagram of the substrate W showing an example cross-sectional structure at the end of the period L1 (step ST22 of the first cycle) (time t22) in FIG. 7 or FIG. 8.

[0094] As shown in FIG. 9A, in the processing in the period H1 (step ST21 of the first cycle), the portion of the silicon-containing film SF exposed through the opening OP is etched in the depth direction (from the top to the bottom in FIG. 9A) to form a recess RC. In the period H1, the silicon-containing film SF is etched until the recess RC reaches a predetermined depth (e.g., 1/n of the thickness of the silicon-containing film SF when n cycles of step ST21 and step ST22 are repeated). In the period H1, as in the period H described above, the silicon-containing film SF is etched at a higher etching rate than in the period L1. This causes the recess RC to be tapered in the depth direction (refer to FIG. 9A).

[0095] In the subsequent period L1 (step ST22 of the first cycle), as in the period L described above, the silicon-containing film SF is etched at a lower etching rate than in the period H1, while the etching proceeds in the horizontal direction, causing the recess RC that is tapered to be close to a rectangular shape (refer to FIG. 9B). More specifically, the recess RC has higher verticality.

[0096] In the example shown in FIG. 7 or FIG. 8, step ST1 (the period H1, period H2, or other periods) to etch the silicon-containing film SF at a high etching rate and step ST2 (the period L1 and period L2) to widen the bottom of the recess RC in the silicon-containing film SF are repeated alternately. This prevents the etching rate from decreasing in step ST2 and increases the verticality of the recess and reduces feature failures in etching.

Modifications

[0097] The embodiments of the present disclosure may be modified in various ways without departing from the spirit and scope of the present disclosure. For example, the embodiment may be modified in the forms described below.

[0098] FIG. 10 is a flowchart of the processing method according to another embodiment. As shown in FIG. 10, the first etching and the second etching may be performed in the opposite order in the etching process. More specifically, the silicon-containing film SF may be first etched using the second process gas (step ST21A), and then may be etched using the first process gas (step ST23A). In step ST2A, the determination as to whether the stop condition is satisfied may be performed between step ST21A and step ST22A, in addition to being performed in step ST23.

# CLAIMS

1. An etching method comprising:

(a) providing a substrate in a chamber, the substrate including a silicon-containing film and a mask on the silicon-containing film; and

(b) etching the silicon-containing film,

(b) including

(b-1) etching the silicon-containing film using plasma generated from a first process gas, the first process gas containing a hydrogen fluoride gas and a reaction control gas to control a reaction between hydrogen fluoride and the silicon-containing film, the first process gas containing, as the reaction control gas, at least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, and

(b-2) etching the silicon-containing film using plasma generated from a second process gas, the second process gas containing a hydrogen fluoride gas, the second process gas containing at least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, or containing no reaction control gas, the reaction accelerator gas contained in the second process gas having a lower partial pressure than the reaction accelerator gas contained in the first process gas, the reaction inhibitor gas contained in the second process gas having a higher partial pressure than the reaction inhibitor gas contained in the first process gas.

2. The etching method according to claim 1, wherein

(b) includes (b-2) performed after (b-1).

3. The etching method according to claim 1, wherein

(b) includes (b-1) performed after (b-2).

4. The etching method according to any one of claims 1 to 3, wherein

(b) includes (b-1) and (b-2) repeated alternately.

5. The etching method according to any one of claims 1 to 3, wherein

(b) includes switching between (b-1) and (b-2) based on at least one of a depth of a recess to be formed in the silicon-containing film by etching, an aspect ratio of the recess, or an etching time of the etching.

6. The etching method according to any one of claims 1 to 3, wherein

(b-1) includes generating the plasma from the first process gas using a pulsed wave of a source radio-frequency signal having a first duty ratio, and

(b-2) includes generating the plasma from the second process gas using a pulsed wave of a source radio-frequency signal having a second duty ratio lower than the first duty ratio.

7. The etching method according to any one of claims 1 to 3, wherein

the reaction accelerator gas is at least one selected from the group consisting of a phosphorus-containing gas, a nitrogen-containing gas, and a hydrogen-containing gas.

8. The etching method according to claim 7, wherein

the phosphorous-containing gas is a phosphorus halide gas.

9. The etching method according to claim 7, wherein

the nitrogen-containing gas is at least one selected from the group consisting of an $NH_3$ gas, an $NF_3$ gas, an NO gas, and an $NO_2$ gas.

10. The etching method according to claim 7, wherein

the hydrogen-containing gas is a gas having a hydroxyl group.

11. The etching method according to any one of claims 1 to 3, wherein

the reaction inhibitor gas is a chlorine-containing gas.

12. The etching method according to claim 11, wherein

the chlorine-containing gas is at least one selected from the group consisting of a $Cl_2$ gas, an $SiCl_2$ gas, an $SiH_2Cl_2$ gas, an $SiCl_4$ gas, an $Si_2Cl_6$ gas, a $CHCl_3$ gas, a $CCl_4$ gas, and a $BCl_3$ gas.

13. The etching method according to any one of claims 1 to 3, wherein

each of the first process gas and the second process gas contains the hydrogen fluoride gas with a highest partial pressure of non-inert components of each of the first process gas and the second process gas.

14. The etching method according to any one of claims 1 to 3, wherein

at least one of the first process gas or the second process gas further includes at least one selected from the group consisting of a carbon-containing gas, an oxygen-containing gas, a

carbon-free fluorine-containing gas, and a halogen-containing gas other than fluorine.

15. The etching method according to any one of claims 1 to 3, wherein

the reaction inhibitor gas contained in the first process gas and the reaction inhibitor gas contained in the second process gas are of the same gas type.

16. The etching method according to any one of claims 1 to 3, wherein

the reaction accelerator gas contained in the first process gas and the reaction accelerator gas contained in the second process gas are of the same gas type.

17. An etching method comprising:

(a) providing a substrate in a chamber, the substrate including a silicon-containing film and a mask on the silicon-containing film; and

(b) etching the silicon-containing film,

(b) including

(b-1) etching the silicon-containing film using plasma containing an active species of hydrogen fluoride generated from a first process gas, the first process gas containing, as a reaction control gas to control a reaction between hydrogen fluoride and the silicon-containing film, at least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, and

(b-2) etching the silicon-containing film using plasma containing an active species of hydrogen fluoride generated from a second process gas, the second process gas containing at

least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, or containing no reaction control gas, the reaction accelerator gas contained in the second process gas having a lower partial pressure than the reaction accelerator gas contained in the first process gas, the reaction inhibitor gas contained in the second process gas having a higher partial pressure than the reaction inhibitor gas contained in the first process gas.

18. The etching method according to claim 17, wherein

the active species of hydrogen fluoride is generated from at least one gas selected from the group consisting of a hydrogen fluoride gas and a hydrofluorocarbon gas.

19. The etching method according to claim 17, wherein

the active species of hydrogen fluoride is generated from a fluoride-containing gas and a hydrogen-containing gas.

20. A plasma processing system, comprising:

a chamber;

a substrate support in the chamber;

a plasma generator; and

a controller, the controller being configured to perform control to cause operations including

(a) placing a substrate on the substrate support in the chamber, the substrate including a silicon-containing film and a mask on the silicon-containing film, and

(b) etching the silicon-containing film,

(b) including

(b-1) etching the silicon-containing film using plasma generated from a first process gas, the first process gas containing a hydrogen fluoride gas and a reaction control gas to control a reaction between hydrogen fluoride and the silicon-containing film, the first process gas containing, as the reaction control gas, at least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, and

(b-2) etching the silicon-containing film using plasma generated from a second process gas, the second process gas containing a hydrogen fluoride gas, the second process gas containing at least one of a reaction accelerator gas to accelerate the reaction or a reaction inhibitor gas to inhibit the reaction, or containing no reaction control gas, the reaction accelerator gas contained in the second process gas having a lower partial pressure than the reaction accelerator gas contained in the first process gas, the reaction inhibitor gas contained in the second process gas having a higher partial pressure than the reaction inhibitor gas contained in the first process gas.