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(54) **Title:** INDEPENDENT CONTROL OF ETCHING AND PASSIVATION GAS COMPONENTS FOR HIGHLY SELECTIVE SILICON OXIDE/SILICON NITRIDE ETCHING

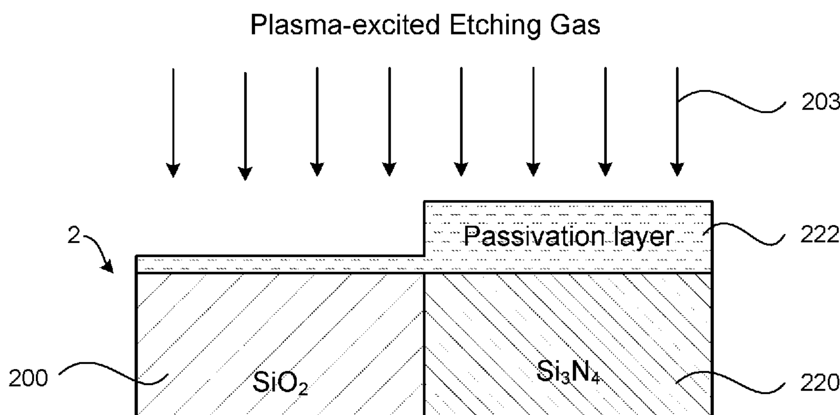

FIG. 2D

(57) **Abstract:** A method for selective plasma etching of silicon oxide relative to silicon nitride is described. The method includes providing a substrate containing a silicon oxide film and a silicon nitride film, and selectively etching the silicon oxide film relative to the silicon nitride film by: a1) exposing the substrate to a plasma-excited passivation gas containing carbon, sulfur, or both carbon and sulfur, where the plasma-excited passivation gas does not contain fluorine or hydrogen, and b1) exposing the substrate to a plasma-excited etching gas containing a fluorine-containing gas. The method can further include, between a1) and b1), an additional step of a2) exposing the substrate to a plasma-excited additional passivation gas containing a fluorocarbon gas, a hydrofluorocarbon gas, a hydrochlorocarbon gas, a hydrochlorofluorocarbon gas, or a hydrocarbon gas, or a combination thereof.

WO 2020/205335 A1

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INDEPENDENT CONTROL OF ETCHING AND PASSIVATION GAS COMPONENTS FOR HIGHLY SELECTIVE SILICON OXIDE/SILICON NITRIDE ETCHING

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CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to and claims priority to United States Provisional Patent Application serial no. 62/830,223 filed on April 5, 2019, the entire contents of which are herein incorporated by reference.

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FIELD OF INVENTION

[0002] The present invention relates to the field of semiconductor manufacturing and semiconductor devices, and more particularly, to a method of selective plasma etching of silicon oxide relative to silicon nitride in semiconductor manufacturing.

15

BACKGROUND OF THE INVENTION

[0003] Next generation semiconductor technology development poses a huge challenge as dry etch removal of one material selective to other materials is needed. Selective silicon oxide etching relative to silicon nitride has many applications and preferential passivation (mostly carbon-based) has been extensively explored for high etch selectivity when using 20 plasmas containing fluorocarbon (FC) or hydrofluorocarbon (HFC) gases. However, many conventional etching methods have limitations that include lack of separate control of the etching component (e.g., fluorine or hydrogen) versus the passivation component (e.g., carbon) in the plasma-excited processing gas. For example, an etching gas containing C_4F_6/C_4F_8 gases contributes to passivation and a passivation gas containing 25 $H_2/CH_2F_2/CH_3F/CH_4$ gases also contributes to etching. Further, many etching methods use only one FC or HFC gas, which provides inadequate flexibility for selectively etching silicon oxide relative to silicon nitride for advanced semiconductor devices. Attempts to fully separate the etching component and the passivation component have not provided full independent control.

30

SUMMARY OF THE INVENTION

[0004] A method of selective plasma etching of silicon oxide relative to silicon nitride in semiconductor manufacturing is disclosed in several embodiments.

[0005] According to one embodiment, the plasma processing method includes providing a substrate containing a silicon oxide film and a silicon nitride film, and selectively etching the silicon oxide film relative to the silicon nitride film by: a1) exposing the substrate to a plasma-excited passivation gas containing carbon, sulfur, or both carbon and sulfur, where the passivation gas does not contain fluorine or hydrogen, and b1) exposing the substrate to a plasma-excited etching gas containing a fluorine-containing gas.

[0006] According to one embodiment, the plasma processing method includes providing a substrate containing a silicon oxide film and a silicon nitride film, and selectively etching the silicon oxide film relative to the silicon nitride film by: a1) exposing the substrate to a plasma-excited passivation gas, wherein the plasma-excited passivation gas includes CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, S_2Cl_2, or a combination thereof, and where the passivation gas does not contain fluorine or hydrogen, and b1) exposing the substrate to a plasma-excited etching gas containing F_2, XeF_2, ClF_3, HF, or NF_3, or a combination thereof.

[0007] According to one embodiment, the plasma processing method includes providing a substrate containing a silicon oxide film and a silicon nitride film, and selectively etching the silicon oxide film relative to the silicon nitride film by: a1) exposing the substrate to a plasma-excited passivation gas, where the plasma excited passivation gas includes CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, or S_2Cl_2, or a combination thereof, and wherein the passivation gas does not contain fluorine or hydrogen, a2) exposing the substrate to a plasma-excited additional passivation gas containing a fluorocarbon gas, a hydrofluorocarbon gas, a hydrochlorocarbon gas, a hydrochlorofluorocarbon gas, a hydrocarbon gas, or a combination thereof, and b1) exposing the substrate to a plasma-excited etching gas containing F_2, XeF_2, ClF_3, HF, NF_3, or a combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] In the accompanying drawings:

[0009] FIG. 1 is a process flow diagram for selective plasma etching of a silicon oxide film relative to a silicon nitride film according to an embodiment of the invention;

5 **[0010]** FIGS. 2A – 2F schematically show through cross-sectional views a method of selective plasma etching of a silicon oxide film relative to a silicon nitride film according to an embodiment of the invention;

[0011] FIG. 3 is a process flow diagram for selective plasma etching of a silicon oxide film relative to a silicon nitride film according to another embodiment of the invention; and

10 **[0012]** FIGS. 4A – 4H schematically show through cross-sectional views a method of selective plasma etching of a silicon oxide film relative to a silicon nitride film according to another embodiment of the invention.

DETAILED DESCRIPTION OF SEVERAL EMBODIMENTS

15 **[0013]** A method of selective plasma etching of silicon oxide relative to silicon nitride is described. The method utilizes independent control of etching and passivation gas components for highly selective silicon oxide/silicon nitride etching.

[0014] The inventive selective plasma etching of silicon oxide relative to silicon nitride described in embodiments of the invention fundamentally differs from conventional silicon 20 oxide or silicon nitride etching process by plasmas containing a fluorocarbon (FC) gas or a hydrofluorocarbon (HFC) gas. In the inventive process, the passivation gas does not contain fluorine or hydrogen species that contribute to etching, but the passivation gas includes a passivation component (carbon, sulfur, or both carbon and sulfur) that shows sufficient volatility difference on silicon oxide versus silicon nitride. The higher volatility of the 25 passivation component on silicon oxide surfaces is thought to be due to the "closed-shell" nature (no unpaired electrons) of carbon by-products on the silicon oxide surfaces, compared to "open-shell" nature (unpaired electrons) of carbon by-products on the silicon nitride surfaces. Further, sulfur-containing etch by-products are thought to be volatile on silicon oxide surfaces but involatile as polymers on silicon nitride surfaces.

30 **[0015]** The etching component is provided using a fluorine-containing gas. According to an embodiment, the fluorine-containing gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas. This full separation of the passivation component and the etching

component greatly enhances the processing window and the etch selectivity between silicon oxide and silicon nitride.

[0016] FIG. 1 is a process flow diagram for selective plasma etching of a silicon oxide film relative to a silicon nitride film according to an embodiment of the invention, and FIGS. 2A – 2F schematically show through cross-sectional views a method of selective plasma etching of a silicon oxide film relative to a silicon nitride film according to an embodiment of the invention.

[0017] Referring now to FIG. 1 and FIG. 2A, the plasma processing method 10 includes, in 12, providing a substrate 1 containing a silicon oxide film 200 (e.g., SiO_2) and a silicon nitride film 220 (e.g., Si_3N_4). In the example shown in FIG. 2A, the silicon oxide film 200 and the silicon nitride film 220 are in the same horizontal plane, but embodiments of the invention may also be applied to films that are not in the same horizontal plane but are offset vertically. Si_3N_4 is the most thermodynamically stable of the silicon nitrides and hence the most commercially important of the silicon nitrides. However, embodiments of the invention may be applied to other silicon nitrides that contain Si and N as the major constituents, where the silicon nitrides can have a wide range of Si and N compositions. Similarly, SiO_2 is the most thermodynamically stable of the silicon oxides and hence the most commercially important of the silicon oxides. However, embodiments of the invention may be applied to other silicon oxides that contain Si and O as the major constituents, where the silicon oxides can have a wide range of Si and O compositions.

[0018] The method further includes, in 14, exposing the substrate 1 to a plasma-excited passivation gas 201 containing carbon, sulfur, or both carbon and sulfur, where the plasma-excited passivation gas 201 does not contain fluorine or hydrogen. This is schematically shown in FIG. 2B. In one example, the plasma-excited passivation gas 201 gas can include CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, or S_2Cl_2, or a combination thereof. The exposure to the plasma-excited passivation gas 201 forms a passivation layer 222 on the substrate 2 as shown in FIG. 2C. The passivation layer 222 is thicker on the silicon nitride film 220 than on the silicon oxide film 200 due to the higher volatility of the by-products of the plasma-excited passivation gas 201 on the silicon oxide film 200 than on the silicon nitride film 220.

[0019] The method further includes, in 16, exposing the substrate to a plasma-excited etching gas 203 containing a fluorine-containing gas. This is schematically shown in FIG. 2D. In one example, plasma-excited etching gas 203 includes F_2, XeF_2, ClF_3, HF, NF_3, or a

combination thereof. The plasma-excited etching gas can optionally further include Ar, He, or a combination thereof. According to an embodiment, the fluorine-containing gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas. The exposure to the plasma-excited etching gas 203 selectively etches the silicon oxide film 200 relative to the silicon
5 nitride film 220 due to the thicker passivation layer 222 on the silicon nitride film 220 than on the silicon oxide film 200. The selective etching is schematically shown in FIG. 2E, where the passivation layer 222 is removed from the silicon oxide film 200 and the silicon oxide film 200 is etched, while the passivation layer 222 on the silicon nitride film 220 is thinned but protects the silicon nitride film 220 from etching.

10 **[0020]** According to one embodiment, the exposing steps 14 and 16 may be performed alternatively and sequentially. Further, as shown by the process arrow 18, the exposing steps 14 and 16 may be repeated at least once to further selectively etch the silicon oxide film 100. According to one embodiment, the exposing steps 14 and 16 may at least partially overlap in time.

15 **[0021]** The method can further include removing the passivation layer 222 from the substrate 2 using an ashing process following the etching process. This is schematically shown in FIG. 2F.

[0022] FIG. 3 is a process flow diagram for selective plasma etching of a silicon oxide film relative to a silicon nitride film according to an embodiment of the invention, and FIGS. 4A –
20 4H schematically show through cross-sectional views a method of selective plasma etching of a silicon oxide film relative to a silicon nitride film according to another embodiment of the invention.

[0023] Referring now to FIG. 3 and FIG. 4A, the plasma processing method 30 includes, in 32, providing a substrate 4 containing a silicon oxide film 400 and a silicon nitride film 420.
25 In the example shown in FIG. 4A, the silicon oxide film 400 and the Si_3N_4 film 420 are in the same horizontal plane, but embodiments of the invention may also be applied to films that are not in the same horizontal plane but are offset vertically.

[0024] The method further includes, in 34, exposing the substrate 4 to a plasma-excited passivation gas 401 containing carbon, sulfur, or both carbon and sulfur, where the
30 passivation gas does not contain fluorine or hydrogen. This is schematically shown in FIG. 4B. In one example, the plasma-excited passivation gas 401 can include CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, S_2Cl_2, or a combination thereof. The exposure to the plasma-

excited passivation gas 401 forms a passivation layer 422 on the substrate 4 as shown in FIG. 4C. The passivation layer 422 is thicker on the silicon nitride film 420 than on the silicon oxide film 400 due to the higher volatility of the by-products of the plasma-excited passivation gas 401 on the silicon oxide film 400 than on the silicon nitride film 420.

5 **[0025]** The method further includes, in 36, exposing the substrate 4 to a plasma-excited additional passivation gas 423 containing a fluorocarbon gas, a hydrofluorocarbon gas, a hydrochlorocarbon gas, a hydrochlorofluorocarbon gas, a hydrocarbon gas, or a combination thereof. In one example, the plasma-excited additional passivation gas can contain CF_2Cl_2, CH_2F_2, CH_4, CH_3F, CHF_3, C_4H_6, C_2H_4, C_3H_6, CH_2Cl_2, CH_3Cl, CH_3Cl, CH_2ClF, $CHCl_2F$, or a

10 combination thereof. The exposure to the plasma-excited additional passivation gas 423 forms an enhanced passivation layer 424 on the substrate 4 as shown in FIG. 4E. The exposure to the plasma-excited additional passivation gas 423 is used for modifying and strengthening the passivation layer 422 without damaging the underlying silicon nitride film 420, since the passivation layer 422 protects the underlying silicon nitride film 420 during the

15 plasma exposure. In one example, the exposure to the plasma-excited additional passivation gas 423 may be performed using low or zero substrate bias to avoid damaging of the silicon nitride film 420 by fluorine or hydrogen ions and/or radicals in the plasma.

[0026] The method further includes, in 38, exposing the substrate 4 to a plasma-excited etching gas 403 containing a fluorine-containing gas. This is schematically shown in FIG.

20 4F. In one example, plasma-excited etching gas 403 includes F_2, XeF_2, ClF_3, HF, NF_3, or a combination thereof. The plasma-excited etching gas can optionally further include Ar, He, or a combination thereof. According to an embodiment, the fluorine-containing gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas. The exposure to the plasma-excited etching gas 402 selectively etches the silicon oxide film 400 relative to the silicon nitride film

25 420 as shown in FIG. 4G.

[0027] The exposure to the plasma-excited etching gas 403 selectively etches the silicon oxide film 400 relative to the silicon nitride film 420 due to the thicker enhanced passivation layer 424 on the silicon nitride film 420 than on the silicon oxide film 400. The selective etching is schematically shown in FIG. 4G, where the enhanced passivation layer 424 is

30 removed from the silicon oxide film 400 and the silicon oxide film 400 is etched, while the enhanced passivation layer 424 on the silicon nitride film 420 is thinned but protects the silicon nitride film 420 from etching.

[0028] According to one embodiment, the exposing steps 34 - 38 may performed alternatively and sequentially. In one example, the exposing steps 34 - 38 may performed alternatively and sequentially in the order: 34, followed by 36, and followed by 38. Further, as shown by the process arrow 40, the exposing steps 34 - 38 may be repeated at least once to further selectively etch the silicon oxide film 400. According to one embodiment, one or more of the exposing steps 34 - 38 may at least partially overlap in time.

[0029] The method can further include removing the enhanced passivation layer 424 from the substrate 4 using an ashing process following the etching process. This is schematically shown in FIG. 4H.

[0030] The method of selective plasma etching of silicon oxide films relative to silicon nitride films may be performed in conventional commercial plasma processing systems, including Inductively Coupled Plasma (ICP) systems, Capacitively Coupled Plasma (CCP) systems, microwave plasma systems, remote plasma systems that generate plasma excited species upstream from the substrate, electron cyclotron resonance (ECR) systems, and other systems.

[0031] The selective silicon oxide/silicon nitride etching process may be performed at substrate temperatures, gas flows, gas flow ratios, and gas pressures that optimize etch selectivity between silicon oxide and silicon nitride. Examples include a substrate temperature between about -200°C and about 200°C, between about -100°C and about 25°C, between about 0°C and about 100°C, between about 0°C and about 200°C, between about -30°C and about 25°C, or between about 0°C and about 25°C. The gas pressure in the plasma etch chamber can between about 5mTorr and about 1000mTorr, between about 10mTorr and 500mTorr, or between about 20mTorr and about 100mTorr. Examples of gas flows are from 0.1 sccm to 500 sccm, with flow ratio of any gas from 0 % to 100 %.

[0032] A plurality of embodiments for a method of selective plasma etching of silicon oxide relative to silicon nitride in semiconductor manufacturing have been described. The foregoing description of the embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. This description and the claims following include terms that are used for descriptive purposes only and are not to be construed as limiting. Persons skilled in the relevant art can appreciate that many modifications and variations are possible in light of the

above teaching. Persons skilled in the art will recognize various equivalent combinations and substitutions for various components shown in the Figures. It is therefore intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

What is claimed is:

1. A plasma processing method, comprising:

providing a substrate containing a silicon oxide film and a silicon nitride film; and selectively etching the silicon oxide film relative to the silicon nitride film by:

a1) exposing the substrate to a plasma-excited passivation gas containing carbon, sulfur, or both carbon and sulfur, wherein the passivation gas does not contain fluorine or hydrogen, and

b1) exposing the substrate to a plasma-excited etching gas containing a fluorine-containing gas.

2. The method of claim 1, wherein step a1) forms a passivation layer that is thicker on the silicon nitride film than on the silicon oxide film.

3. The method of claim 1, wherein the exposing steps a1) and b1) are performed alternatively and sequentially.

4. The method of claim 3, further comprising

repeating the exposing steps a1) and b1) at least once to further selectively etch the silicon oxide film.

5. The method of claim 1, wherein the exposing steps a1) and b1) at least partially overlap in time.

6. The method of claim 1, wherein the plasma-excited etching gas includes F_2, XeF_2, ClF_3, HF, NF_3, or a combination thereof.

7. The method of claim 1, wherein the plasma-excited etching gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas.

8. The method of claim 1, wherein the plasma-excited etching gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas.

9. The method of claim 1, wherein the plasma excited passivation gas includes CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, S_2Cl_2, or a combination thereof.

10. The method of claim 1, wherein the silicon oxide film includes SiO_2 and the silicon nitride film includes Si_3N_4.

11. The method of claim 1, further comprising:

a2) exposing the substrate to a plasma-excited additional passivation gas containing a fluorocarbon gas, a hydrofluorocarbon gas, a hydrochlorocarbon gas, a hydrochlorofluorocarbon gas, a hydrocarbon gas, or a combination thereof.

12. The method of claim 11, wherein the plasma-excited additional passivation gas contains CF_2Cl_2, CH_2F_2, CH_4, CH_3F, CHF_3, C_4H_6, C_2H_4, C_3H_6, CH_2Cl_2, CH_3Cl, CH_3Cl, CH_2ClF, $CHCl_2F$, or a combination thereof.

13. The method of claim 11, wherein the exposing steps a1), a2), and b1) are performed alternatively and sequentially in the order a1), followed by a2), and followed by b1).

14. The method of claim 11, further comprising:

alternatively and sequentially repeating the exposing steps a1), a2), and b1) at least once to further selectively etch the silicon oxide film.

15. The method of claim 11, wherein the exposing steps a1), a2), and b1) at least partially overlap in time.

16. A plasma processing method, comprising:

providing a substrate containing a silicon oxide film and a silicon nitride film; and

selectively etching the silicon oxide film relative to the silicon nitride film by:

a1) exposing the substrate to a plasma-excited passivation gas, wherein the plasma excited passivation gas includes CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, S_2Cl_2, or a combination thereof, and wherein the passivation gas does not contain fluorine or hydrogen, and

b1) exposing the substrate to a plasma-excited etching gas containing F_2, XeF_2, ClF_3, HF, NF_3, or a combination thereof.

17. The method of claim 16, wherein the plasma-excited etching gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas.

18. A plasma processing method, comprising:

providing a substrate containing a silicon oxide film and a silicon nitride film; and selectively etching the silicon oxide film relative to the silicon nitride film by:

a1) exposing the substrate to a plasma-excited passivation gas, wherein the plasma excited passivation gas includes CO, COS, CS_2, CCl_4, C_2Cl_4, CCl_2Br_2, SCl_2, or S_2Cl_2, or a combination thereof, and wherein the passivation gas does not contain fluorine or hydrogen,

a2) exposing the substrate to a plasma-excited additional passivation gas containing a fluorocarbon gas, a hydrofluorocarbon gas, a hydrochlorocarbon gas, a hydrochlorofluorocarbon gas, a hydrocarbon gas, or a combination thereof, and

b1) exposing the substrate to a plasma-excited etching gas containing F_2, XeF_2, ClF_3, HF, NF_3, or a combination thereof.

19. The method of claim 18, wherein the plasma-excited additional passivation gas contains CF_2Cl_2, CH_2F_2, CH_4, CH_3F, CHF_3, C_4H_6, C_2H_4, C_3H_6, CH_2Cl_2, CH_3Cl, CH_3Cl, CH_2ClF, $CHCl_2F$, or a combination thereof.

20. The method of claim 18, wherein the plasma-excited etching gas does not contain a fluorocarbon gas or a hydrofluorocarbon gas.

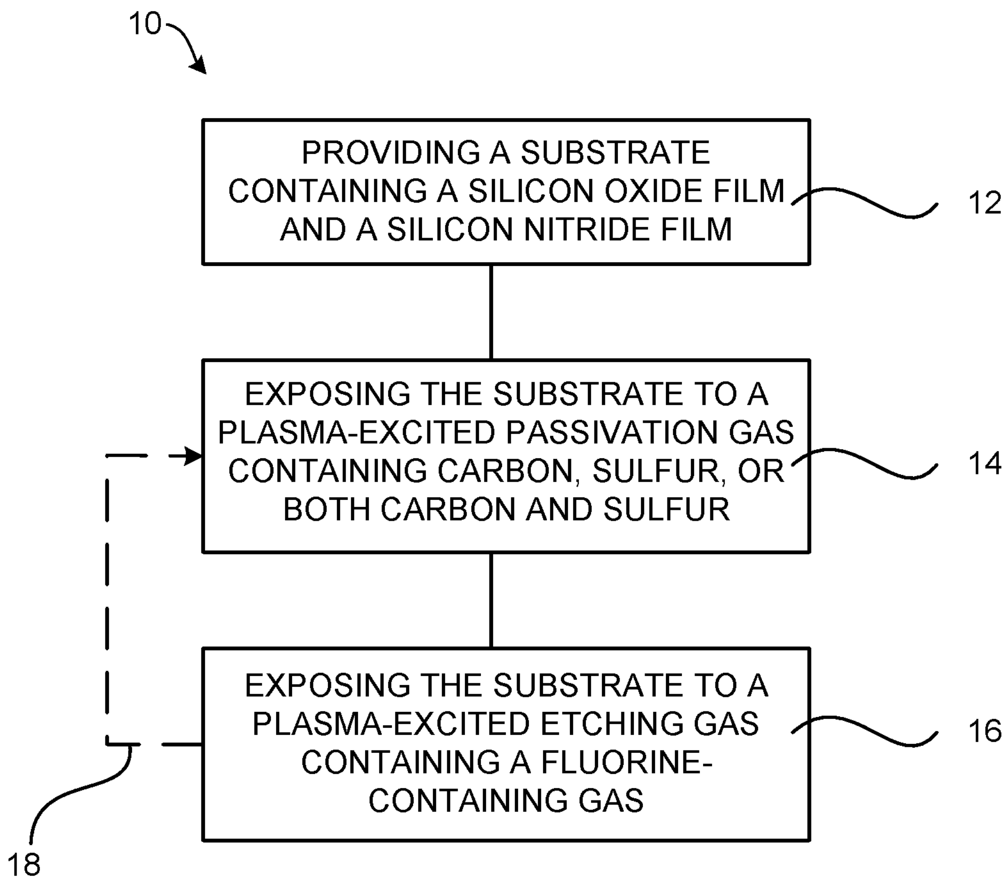

FIG. 1

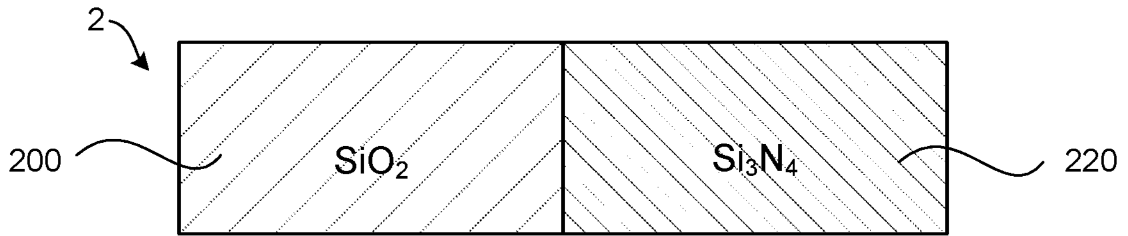

FIG. 2A

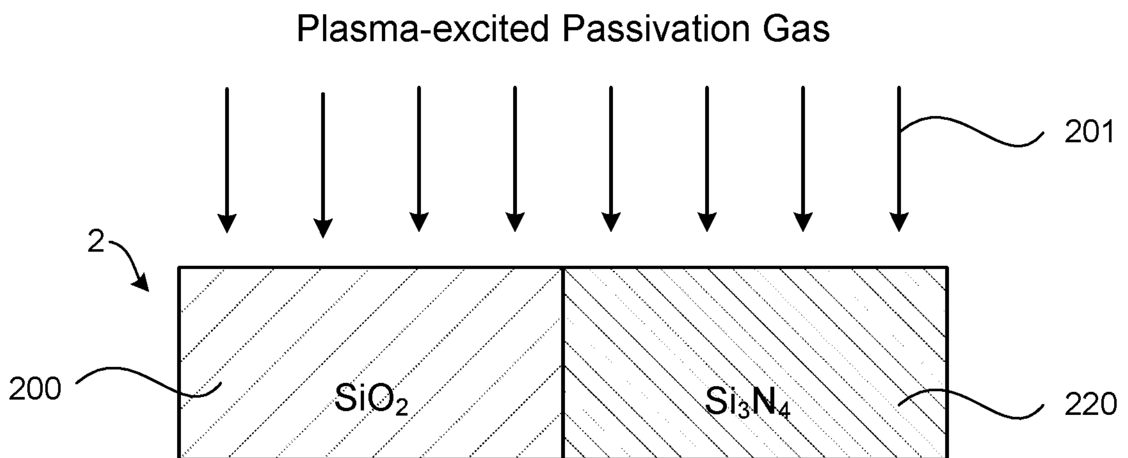

FIG. 2B

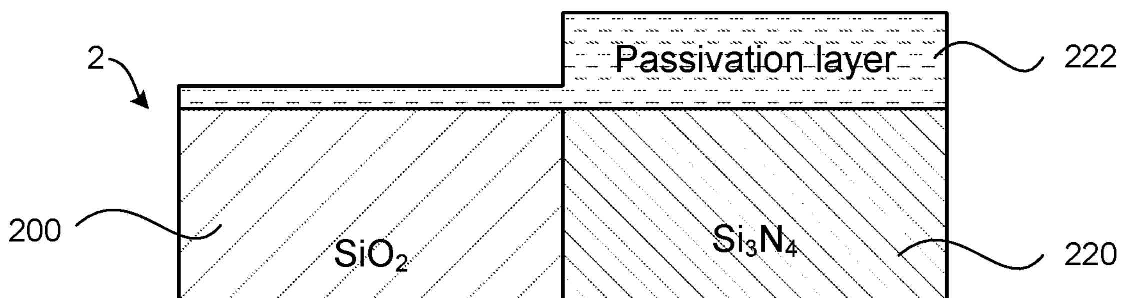

FIG. 2C

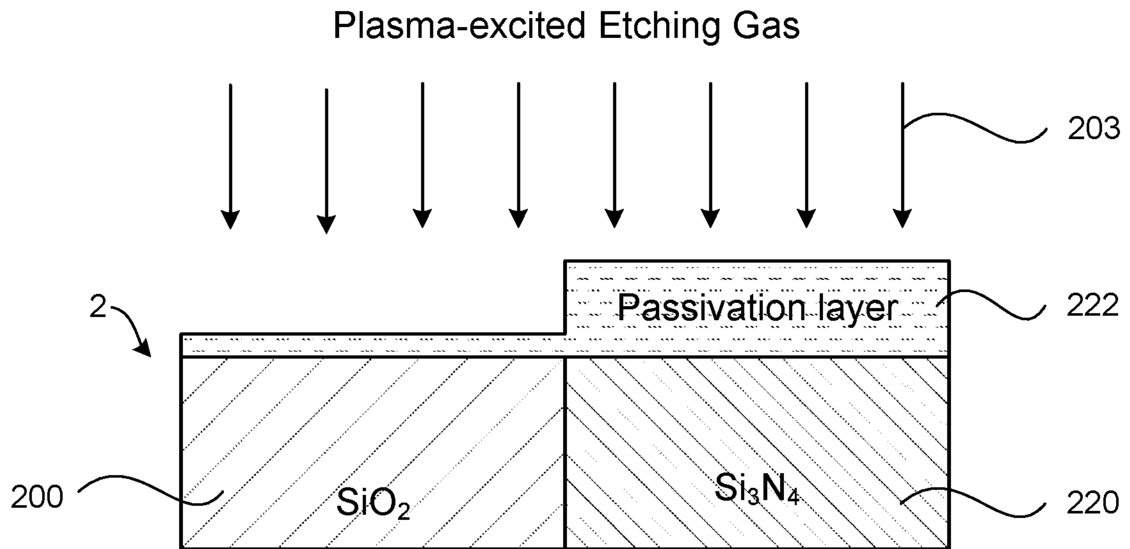

FIG. 2D

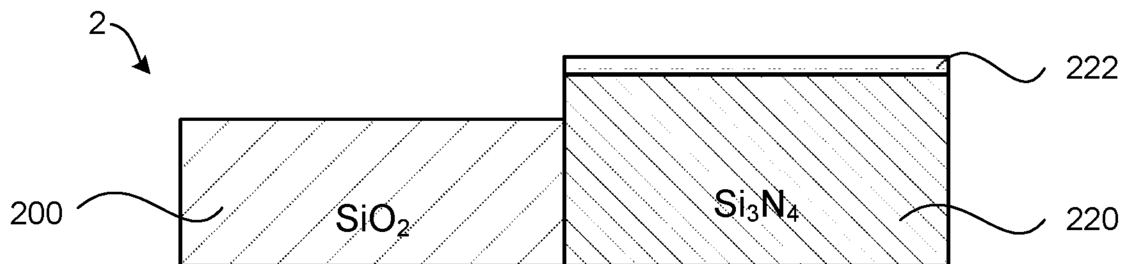

FIG. 2E

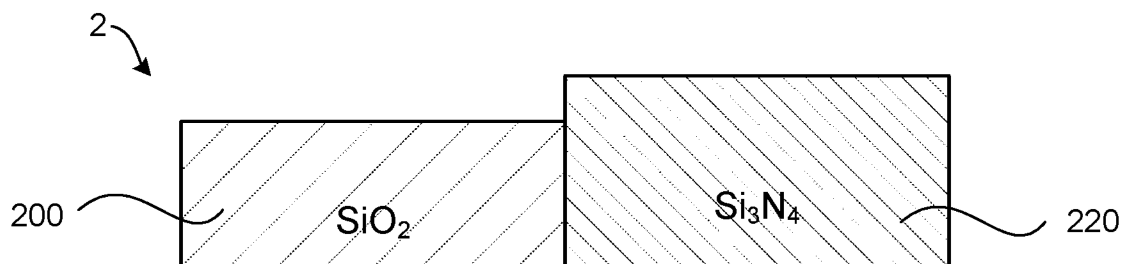

FIG. 2F

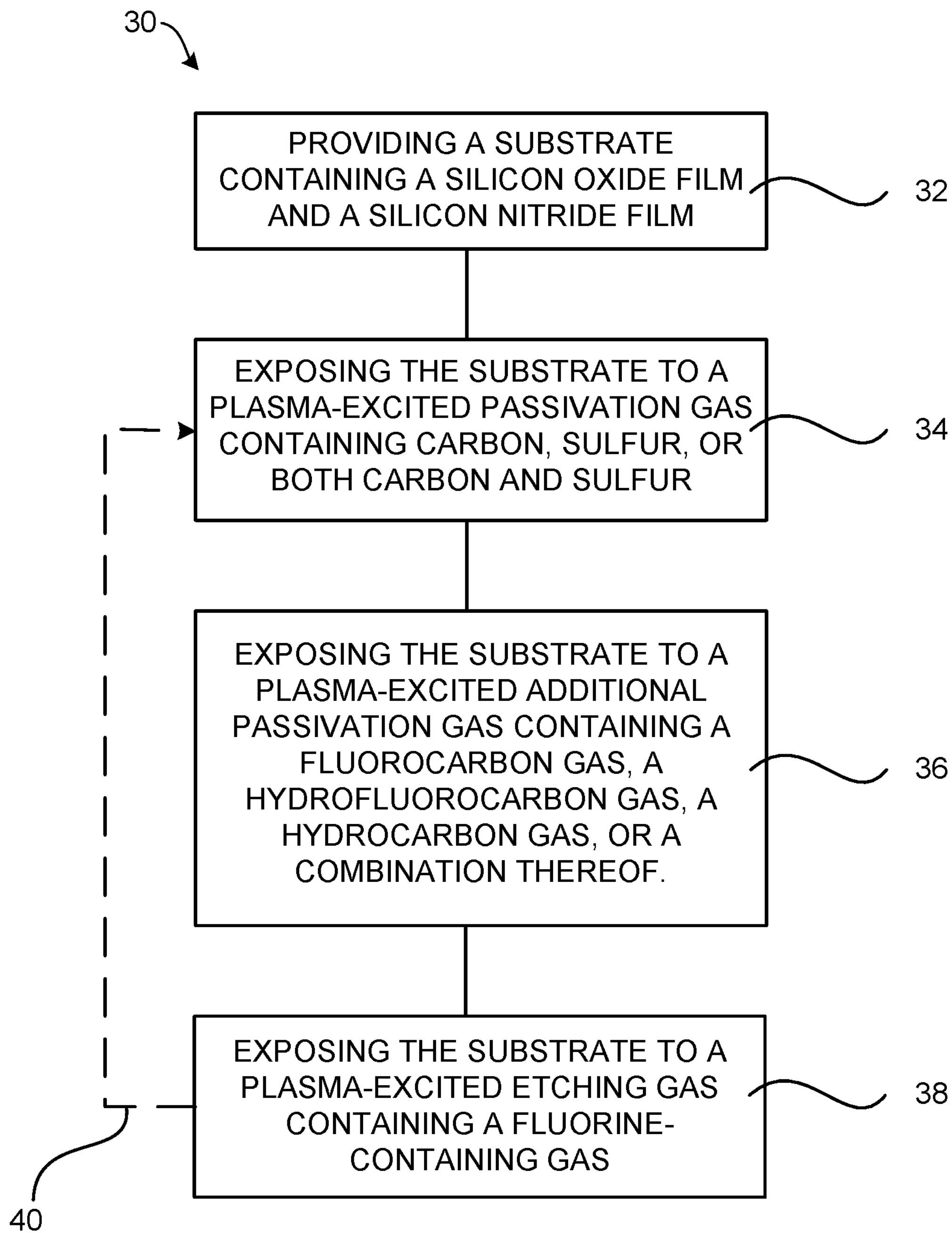

FIG. 3

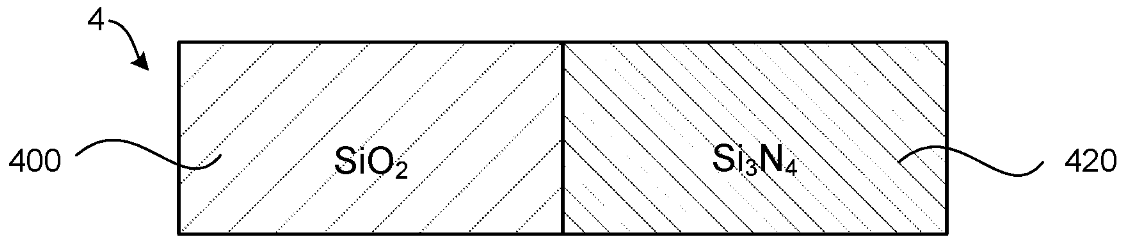

FIG. 4A

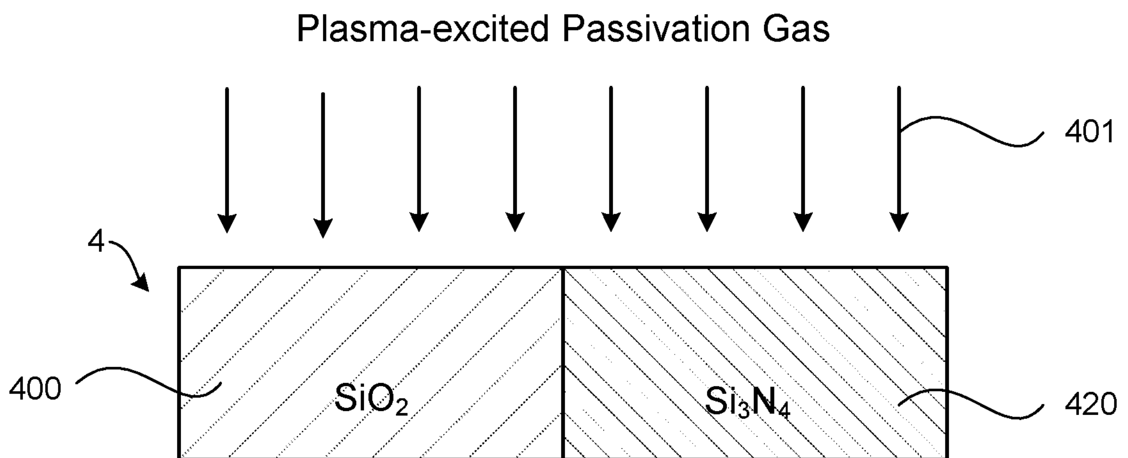

FIG. 4B

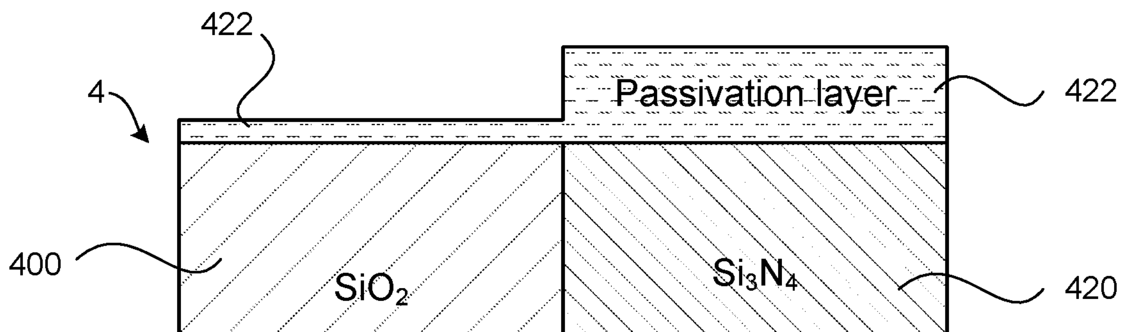

FIG. 4C

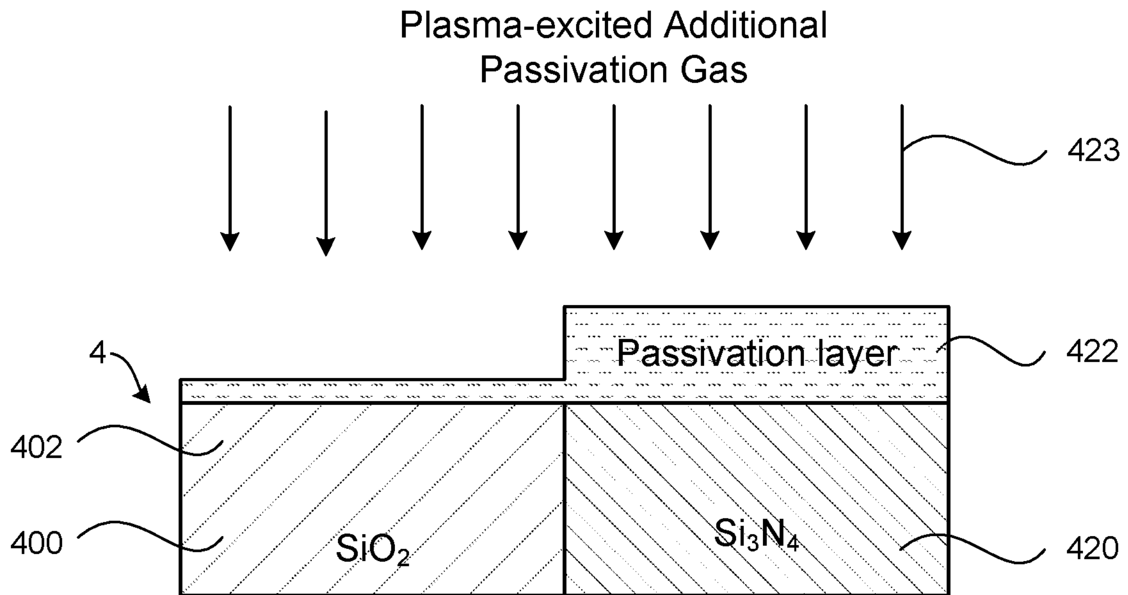

FIG. 4D

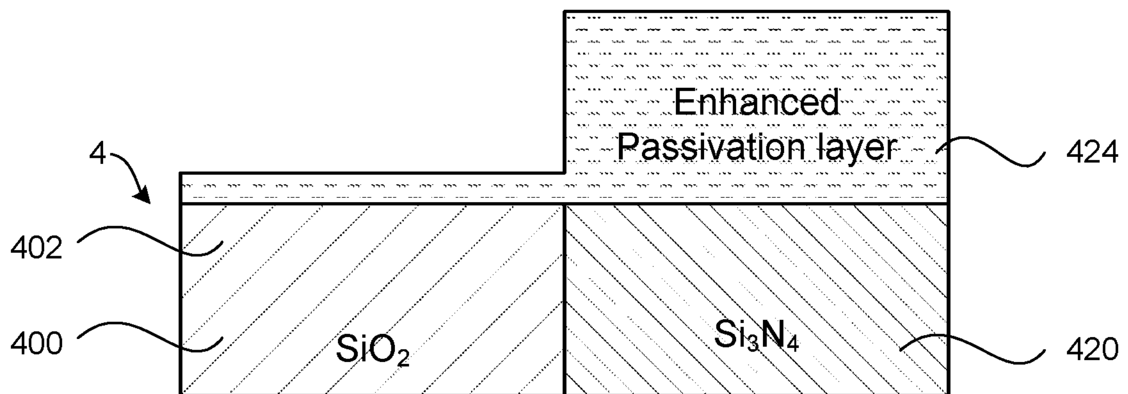

FIG. 4E

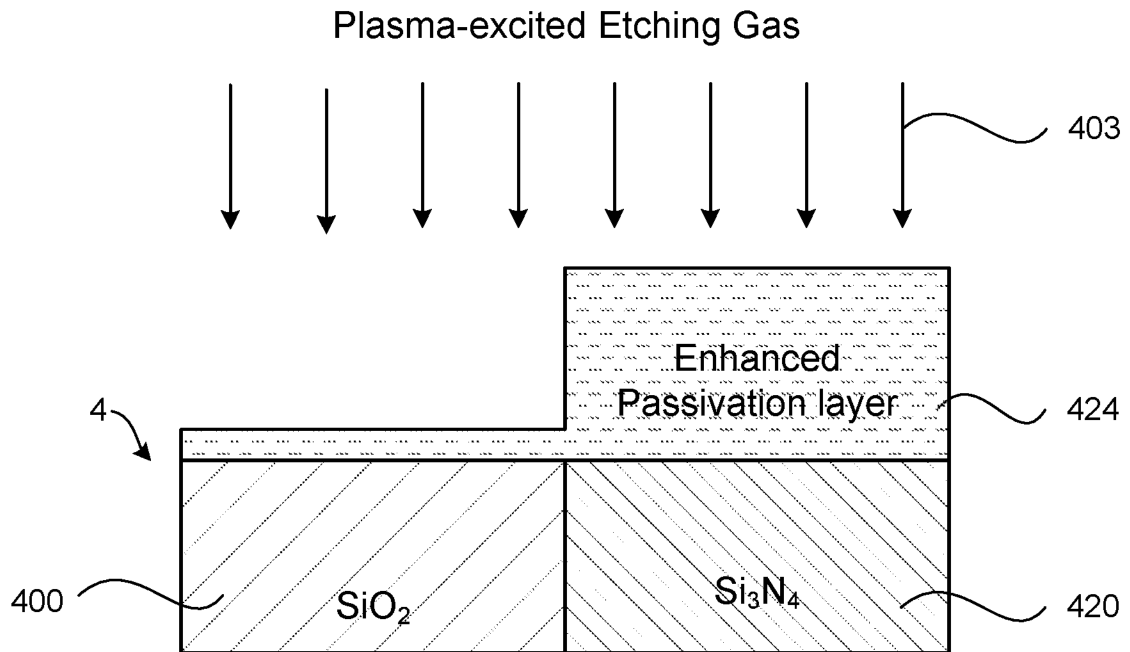

FIG. 4F

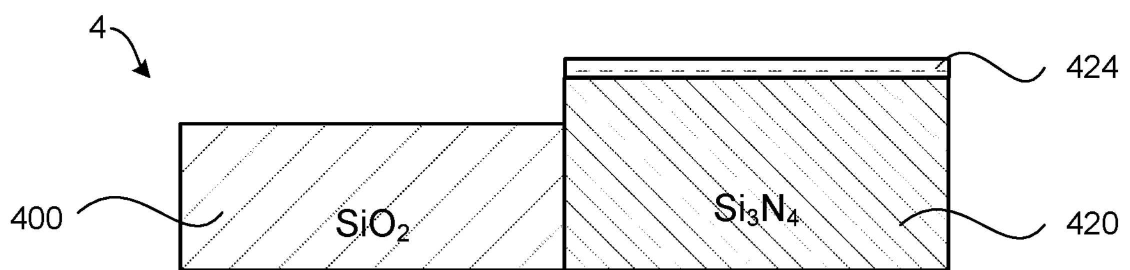

FIG. 4G

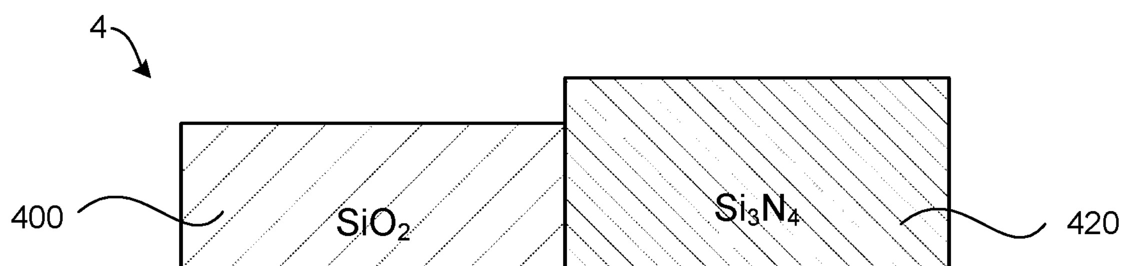

FIG. 4H

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/024446

A. CLASSIFICATION OF SUBJECT MATTER

H01L 21/311(2006.01)i, H01L 21/02(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L 21/311; H01L 21/3065; H01L 21/3213; H01L 21/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: silicon-oxide, selectively, etching, passivation, independent-control

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2016-0247691 A1 (TOKYO ELECTRON LIMITED) 25 August 2016 Claim 1; and figures 1, 8-11.	1-20
A	US 2016-0064247 A1 (TOKYO ELECTRON LIMITED) 03 March 2016 Paragraphs 19, 40; claim 1; and figures 3A-3C.	1-20
A	WO 2019-027811 A1 (LAM RESEARCH CORPORATION) 07 February 2019 Paragraphs 59-60; and figures 3A-3G.	1-20
A	US 2014-0308817 A1 (TOKYO ELECTRON LIMITED) 16 October 2014 Paragraphs 36-43; claim 1; and figures 1-5B.	1-20
A	KR 10-2016-0126890 A (LAM RESEARCH CORPORATION) 02 November 2016 Paragraph 41; and figures 2a-2d.	1-20

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents:
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 July 2020 (16.07.2020)	**17 July 2020 (17.07.2020)**

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