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Komatani

(54) **METHOD FOR FABRICATING SEMICONDUCTOR DEVICE**

(71) Applicant: **SUMITOMO ELECTRIC DEVICE INNOVATIONS, INC.**, Yokohama-shi (JP)

(72) Inventor: **Tsutomu Komatani**, Yokohama-shi (JP)

(73) Assignee: **SUMITOMO ELECTRIC DEVICE INNOVATIONS, INC.**, Yokohama-shi (JP)

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USPC **438/186**

(57) **ABSTRACT**

A method for fabricating a semiconductor device includes: forming a first film on a nitride semiconductor layer so as to contact the nitride semiconductor layer and have a thickness equal to or larger than 1 nm and equal to or smaller than 5 nm, the first film being made of silicon nitride having a composition ratio of silicon to nitrogen larger than 0.75, silicon oxide having a composition ratio of silicon to oxygen larger than 0.5, or aluminum; and forming a source electrode, a gate electrode and a drain electrode on the nitride semiconductor layer.

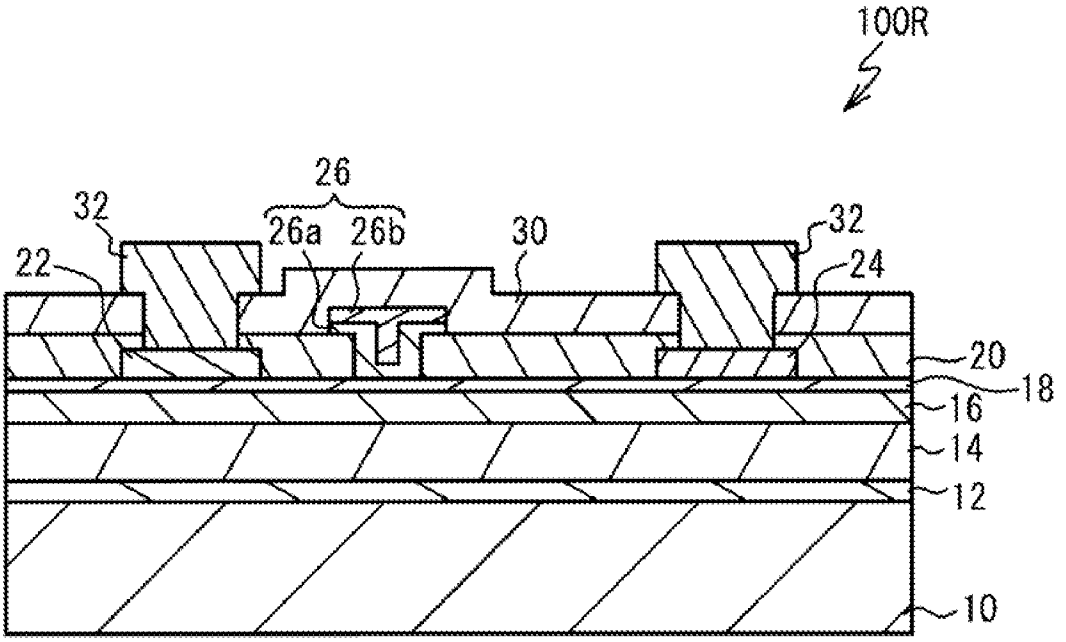


FIG. 1

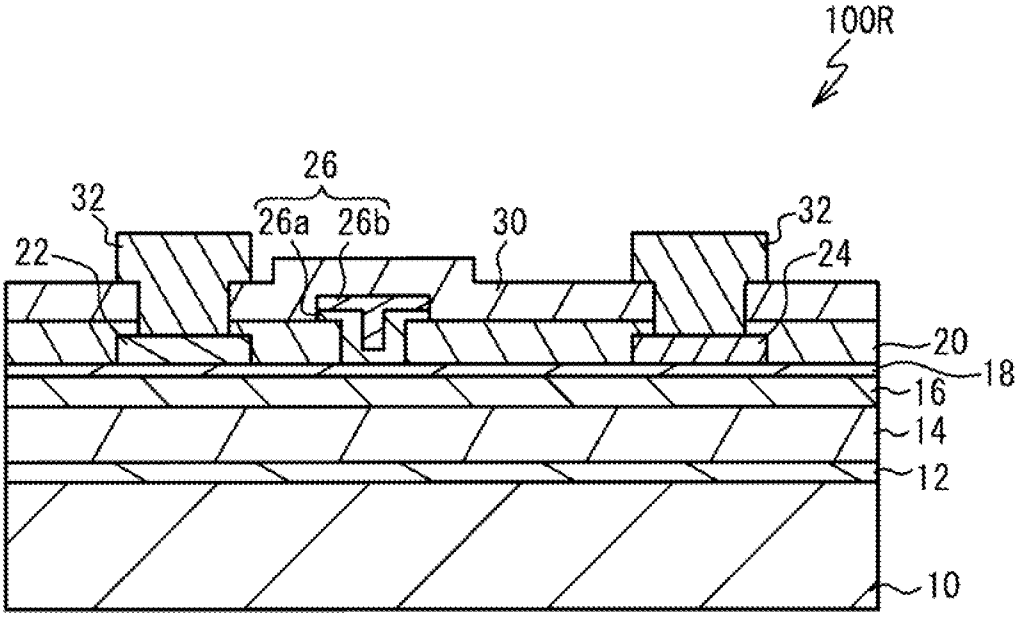


FIG. 2A

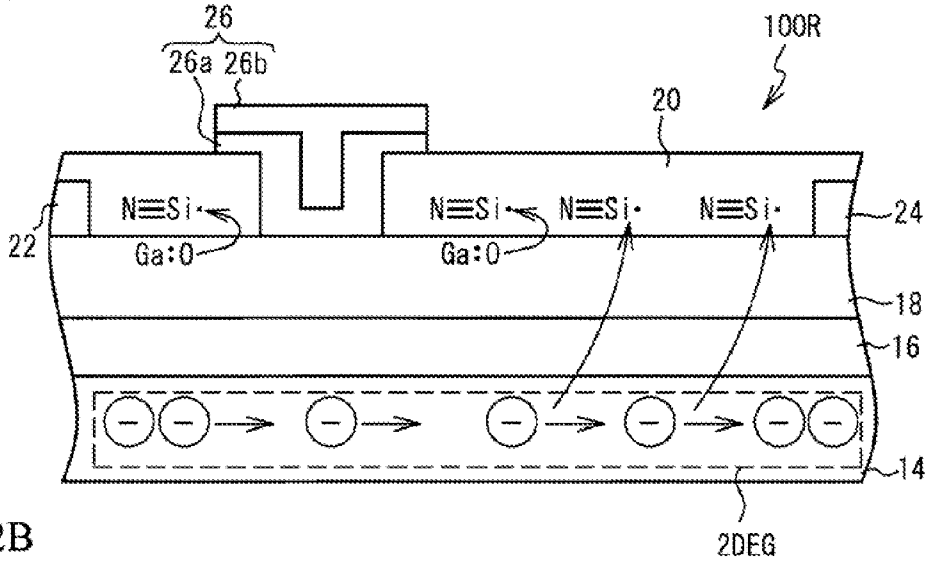

26
26a 26b
100R
20
22
N≡Si
Ga:O
N≡Si
Ga:O
N≡Si
N≡Si
24
18
16
14
2DEG

FIG. 2B

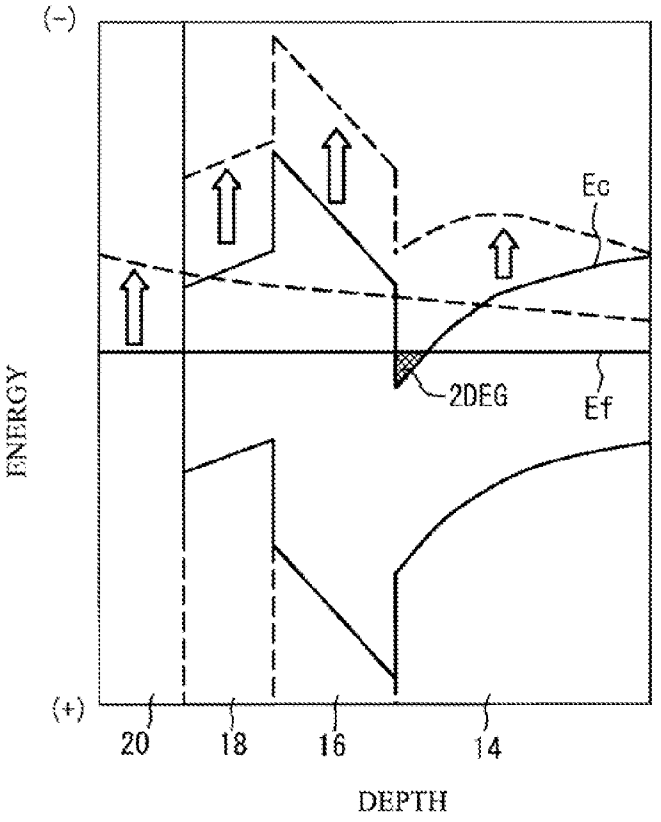

(−)
Ec
2DEG
Ef
ENERGY
(+)
20
18
16
14
DEPTH

FIG. 3

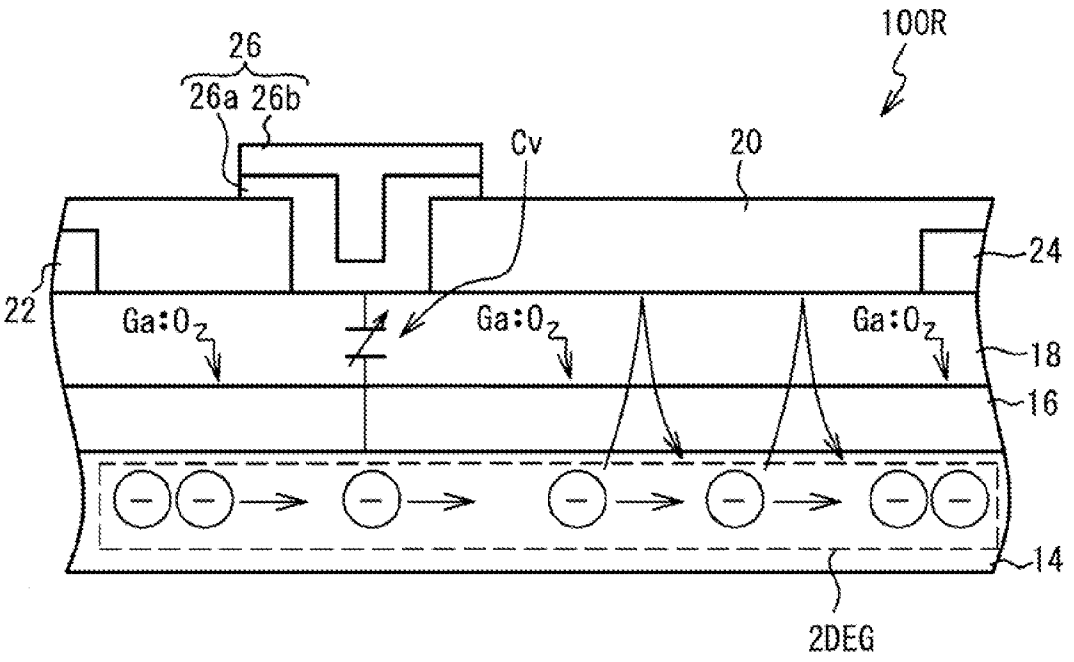
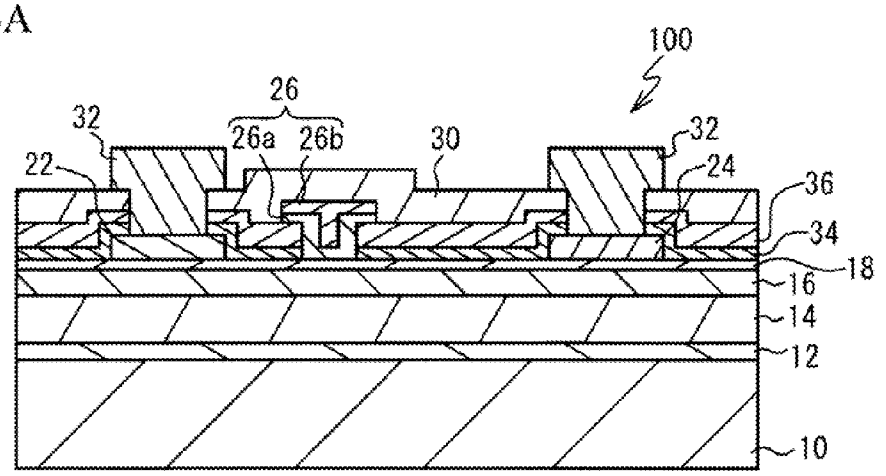


FIG. 4A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26
26a
26b
32
32
22
30
24
36
34
18
16
14
12
10

FIG. 4B

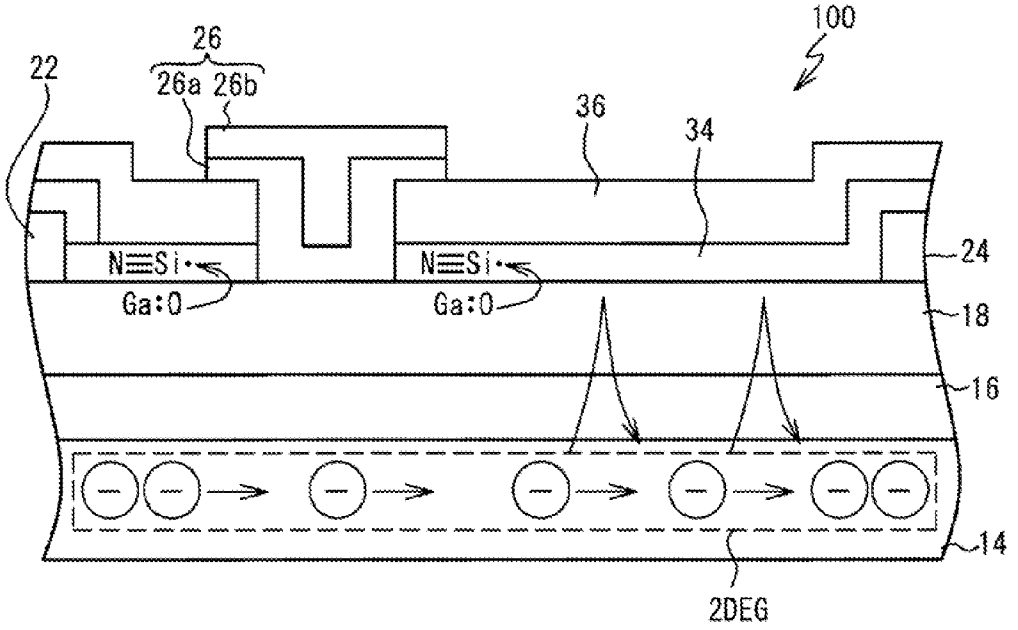

100
26
26a
26b
22
36
34
N≡Si
N≡Si
Ga:O
Ga:O
24
18
16
14
2DEG

FIG. 5A

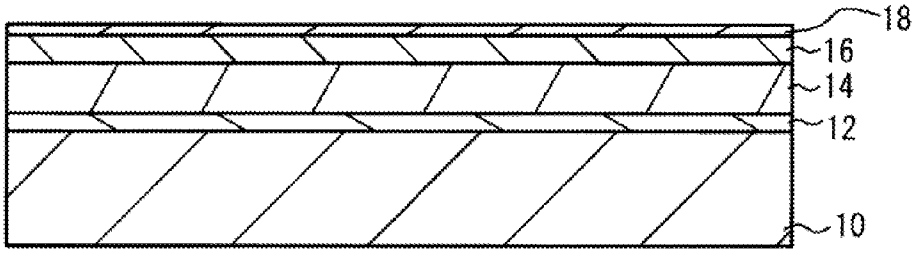


FIG. 5B

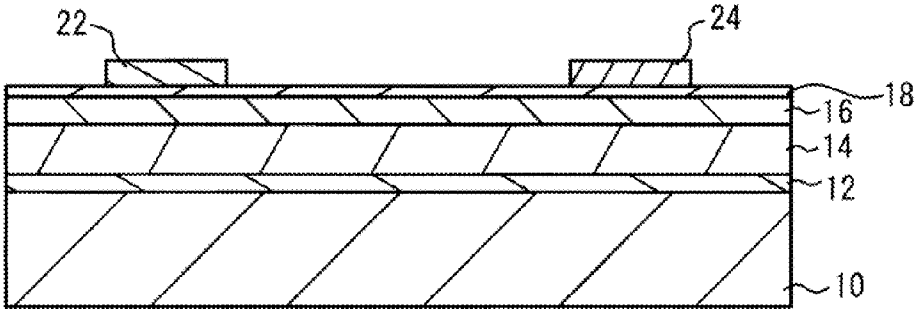


FIG. 5C

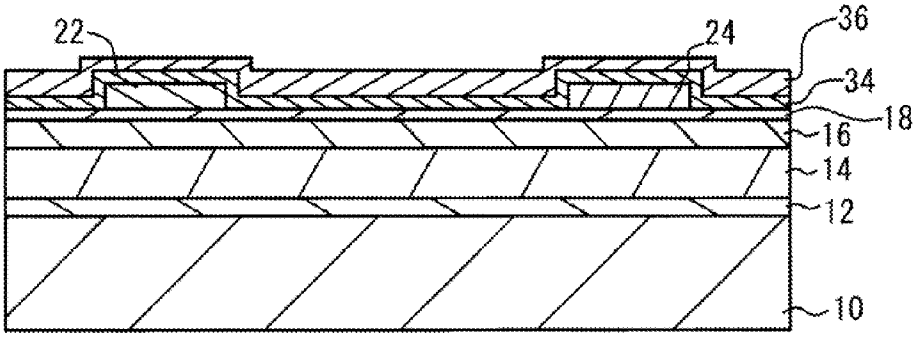


FIG. 6A

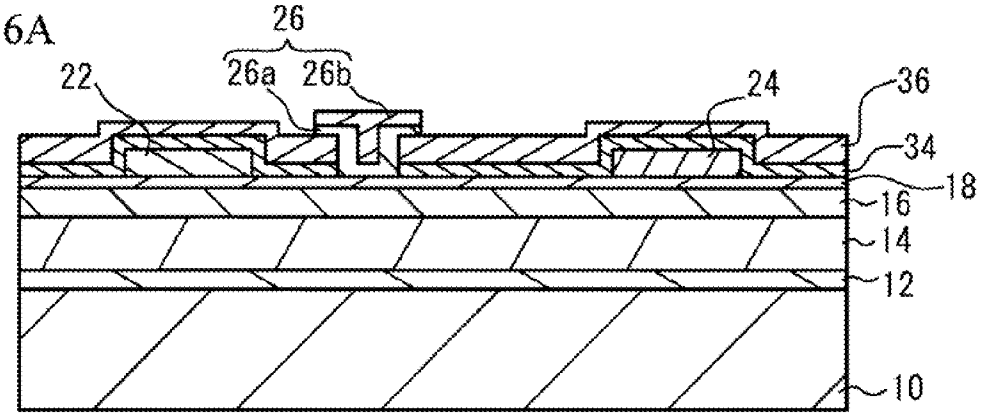


FIG. 6B

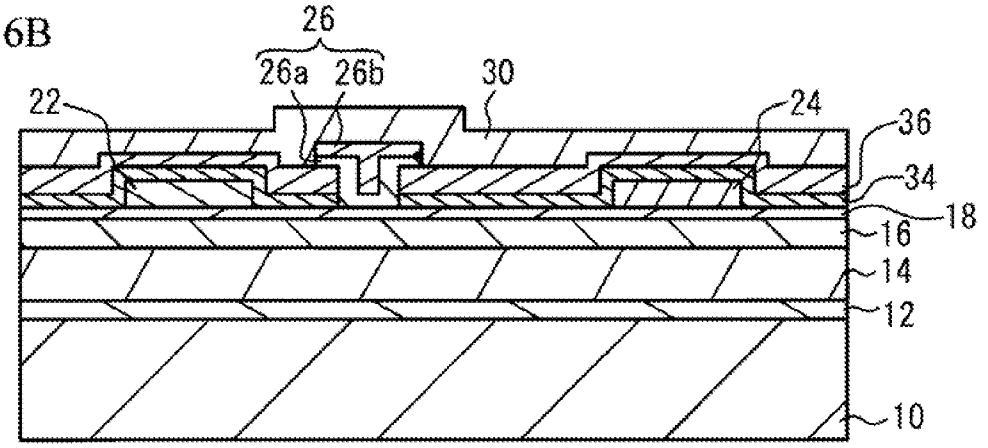


FIG. 6C

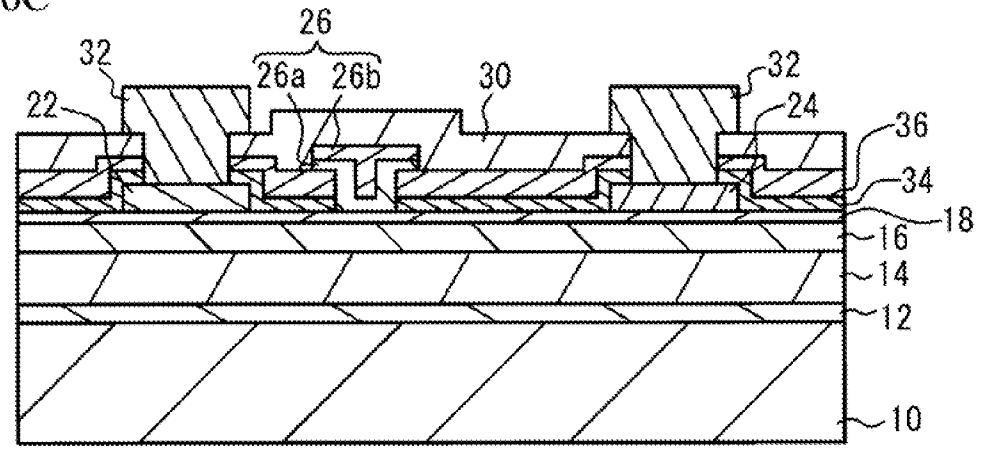


FIG. 7A

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
BTBAS	NH3 plasma or N2 plasma	0.03-0.5	2-60	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.03-0.5	2-30	0.2-5	2-15	1800

FIG. 7B

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
TDMAS	NH3 plasma or N2 plasma	0.02-0.5	2-40	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.02-0.5	2-20	0.2-5	2-15	1800

FIG. 8A

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
DMS	NH3 plasma or N2 plasma	0.01-0.2	2-30	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.01-0.2	2-15	0.2-5	2-15	1800

FIG. 8B

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
BEMAS	NH3 plasma or N2 plasma	0.03-0.5	2-60	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.03-0.5	2-30	0.2-5	2-15	30

FIG. 9A

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
SiCl4	NH3 plasma or N2 plasma	0.01-0.2	2-30	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.01-0.2	2-15	0.2-5	2-15	1800

FIG. 9B

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
Si2Cl6	NH3 plasma or N2 plasma	0.01-0.2	2-30	0-0.1	0-15	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.01-0.2	2-15	0.2-5	2-15	1800

FIG. 10A

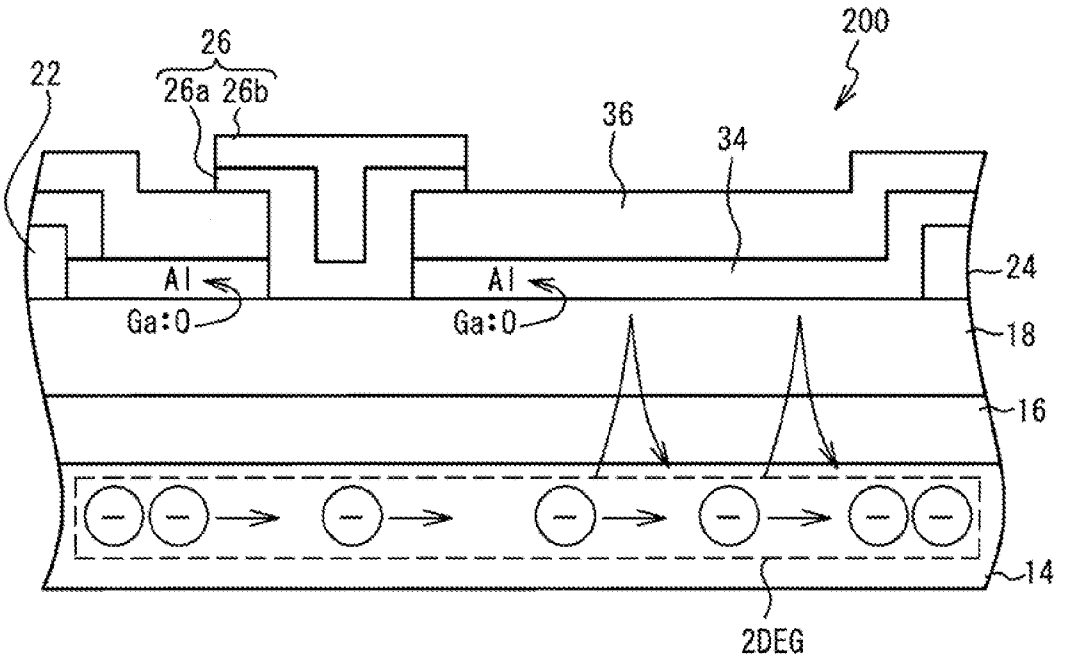


FIG. 10B

source gas	supply time (sec)	1st exhaust time (sec)	number of cycles
TMA	0.01-0.2	2-30	30

FIG. 11

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
BTBAS	O2 plasma	0.03-0.5	2-60	0-0.3	0-15	45
	O3	0.03-0.5	2-60	0-1.5	0-15	45
	H2O	0.03-0.5	2-60	0	0	45
	Lewis base	0.03-0.5	2-60	0	0	45
		2nd film 36				
	2nd source gas	supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.03-0.5	2-30	0.5-5	2-15	1800
	O3	0.03-0.5	2-30	2-5	2-15	1800
	H2O	0.03-0.5	2-30	0.1-2	2-15	1800
	Lewis base	0.03-0.5	2-30	0.1-5	2-15	1800

FIG. 12

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
TDMAS	O2 plasma	0.02-0.5	2-40	0-0.3	0-15	45
	O3	0.02-0.5	2-40	0-1.5	0-15	45
	H2O	0.02-0.5	2-40	0	0	45
	Lewis base	0.02-0.5	2-40	0	0	45
		2nd film 36				
	2nd source gas	supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.02-0.5	2-20	0.5-5	2-15	1800
	O3	0.02-0.5	2-20	2-5	2-15	1800
	H2O	0.02-0.5	2-20	0.1-2	2-15	1800
	Lewis base	0.02-0.5	2-20	0.1-5	2-15	1800

FIG. 13

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
DMS	O2 plasma	0.01-0.2	2-30	0-0.3	0-15	45
	O3	0.01-0.2	2-30	0-1.5	0-15	45
	H2O	0.01-0.2	2-30	0	0	45
	Lewis base	0.01-0.2	2-30	0	0	45
	2nd source gas	2nd film 36				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.01-0.2	2-15	0.5-5	2-15	1800
	O3	0.01-0.2	2-15	2-5	2-15	1800
	H2O	0.01-0.2	2-15	0.1-2	2-15	1800
	Lewis base	0.01-0.2	2-15	0.1-5	2-15	1800

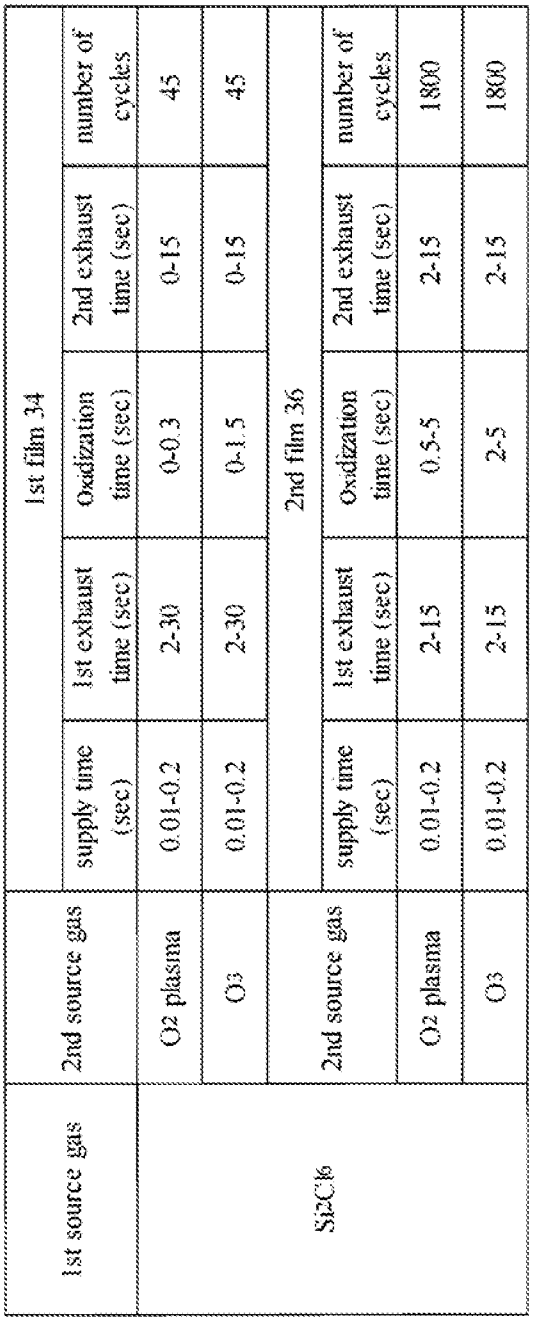
FIG. 14

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
BEMAS	O2 plasma	0.03-0.5	2-60	0-0.3	0-15	45
	O3	0.03-0.5	2-60	0-1.5	0-15	45
	H2O	0.03-0.5	2-60	0	0	45
	Lewis base	0.03-0.5	2-60	0	0	45
	2nd source gas	2nd film 36				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.03-0.5	2-30	0.5-5	2-15	1800
	O3	0.03-0.5	2-30	2-5	2-15	1800
	H2O	0.03-0.5	2-30	0.1-2	2-15	1800
	Lewis base	0.03-0.5	2-30	0.1-5	2-15	1800

FIG. 15

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
SiCl4	O2 plasma	0.01-0.2	2-30	0-0.3	0-15	45
	O3	0.01-0.2	2-30	0-1.5	0-15	45
	2nd source gas	2nd film 36				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.01-0.2	2-15	0.5-5	2-15	1800
	O3	0.01-0.2	2-15	2-5	2-15	1800

FIG. 16

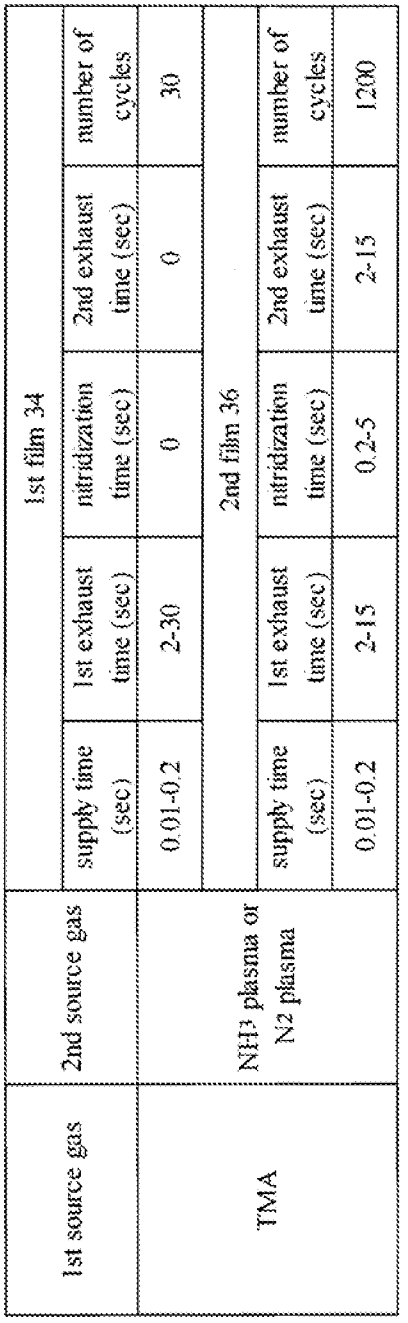


1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
Si2Cl6	O2 plasma	0.01-0.2	2-30	0-0.3	0-15	45
	O3	0.01-0.2	2-30	0-1.5	0-15	45
		2nd film 36				
	2nd source gas	supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.01-0.2	2-15	0.5-5	2-15	1800
	O3	0.01-0.2	2-15	2-5	2-15	1800

FIG. 17

1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
TMA	O2 plasma	0.01-0.2	2-30	0-0.3	0-15	30
	O3	0.01-0.2	2-30	0-1.5	0-15	30
	H2O	0.01-0.2	2-30	0	0	30
	Lewis base	0.01-0.2	2-30	0	0	30
	2nd source gas	2nd film 36				
		supply time (sec)	1st exhaust time (sec)	Oxidization time (sec)	2nd exhaust time (sec)	number of cycles
	O2 plasma	0.01-0.2	2-15	0.5-5	2-15	1200
	O3	0.01-0.2	2-15	2-5	2-15	1200
	H2O	0.01-0.2	2-15	0.1-2	2-15	1200
	Lewis base	0.01-0.2	2-15	0.1-5	2-15	1200

FIG. 18



1st source gas	2nd source gas	1st film 34				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
TMA	NH3 plasma or N2 plasma	0.01-0.2	2-30	0	0	30
		2nd film 36				
		supply time (sec)	1st exhaust time (sec)	nitridization time (sec)	2nd exhaust time (sec)	number of cycles
		0.01-0.2	2-15	0.2-5	2-15	1200

METHOD FOR FABRICATING SEMICONDUCTOR DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2012-081797 filed on Mar. 30, 2012, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0002] (i) Technical Field

[0003] The present invention relates to a method for fabricating a semiconductor device.

[0004] (ii) Related Art

[0005] Nitride semiconductors are used in semiconductor devices such as an FET (Field Effect Transistor). In order to protect a nitride semiconductor layer, an insulating layer that covers the nitride semiconductor layer may be provided. For example, Japanese Patent Application Publication No. 2010-166040 discloses an arrangement in which a protection film made of silicon oxide is provided on a nitride semiconductor layer.

[0006] Conventionally, the capacitance of the semiconductor device, which may include the intrinsic capacitance and the parasitic capacitance, may change due to an oxide layer formed on the surface of the nitride semiconductor layer. Variation in the capacitance may drift the gain. Further, electrons are captured in electron traps in the insulating film, so that the current of the semiconductor device may change. Conventionally, it is difficult to suppress both variation in the capacitance and that in the current.

SUMMARY

[0007] According to an aspect of the present invention, it is possible to suppress both variation in the capacitance and that in the current.

[0008] According to another aspect of the present invention, there is provided a method for fabricating a semiconductor device including: forming a first film that contact a surface of the nitride semiconductor layer and have a thickness equal to or larger than 1 nm and equal to or smaller than 5 nm, the first film being made of silicon nitride having a composition ratio of silicon to nitrogen larger than 0.75, silicon oxide having a composition ratio of silicon to oxygen larger than 0.5, or aluminum; and forming a source electrode, a gate electrode and a drain electrode on the nitride semiconductor layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a cross-sectional view of a semiconductor device in accordance with a comparative example;

[0010] FIG. **2**A is a schematic view that illustrates an example in which an insulating film (silicon nitride) has a large Si composition ratio, and FIG. **2**B is a band diagram of the example;

[0011] FIG. **3** is a schematic diagram of an exemplary structure in which an insulating film has a stoichiometric composition;

[0012] FIG. **4**A is a cross-sectional view of a semiconductor device in accordance with a first embodiment, and FIG. **4**B is a diagram that schematically illustrates an enlarged view of a gate electrode and its vicinity;

[0013] FIGS. **5**A through **5**C are cross-sectional views of an exemplary method for fabricating a semiconductor device;

[0014] FIGS. **6**A through **6**C are cross-sectional views of steps of the method that follow the steps of FIGS. **5**A through **5**C;

[0015] FIGS. **7**A and **7**B illustrate conditions for growing first and second films formed of silicon nitride;

[0016] FIGS. **8**A and **8**B illustrate conditions for growing first and second films formed of silicon nitride;

[0017] FIGS. **9**A and **9**B illustrate conditions for growing first and second films formed of silicon nitride;

[0018] FIG. **10**A is a schematic diagram of an enlarged view of a gate electrode of a semiconductor device in accordance with a second embodiment, and FIG. **10**B illustrates conditions for growing a first film of aluminum;

[0019] FIG. **11** illustrates conditions for growing first and second films formed of silicon oxide;

[0020] FIG. **12** illustrates conditions for growing first and second films formed of silicon oxide;

[0021] FIG. **13** illustrates conditions for growing first and second films formed of silicon oxide;

[0022] FIG. **14** illustrates conditions for growing first and second films formed of silicon oxide;

[0023] FIG. **15** illustrates conditions for growing first and second films formed of silicon oxide;

[0024] FIG. **16** illustrates conditions for growing first and second films formed of silicon oxide;

[0025] FIG. **17** illustrates conditions for growing a first film of aluminum and a second film of aluminum oxide; and

[0026] FIG. **18** illustrates conditions for growing a first film of aluminum and a second film of aluminum nitride.

DETAILED DESCRIPTION

[0027] First, a comparative example is described. FIG. **1** is a cross-sectional view of a semiconductor device **100**R in accordance with a comparative example.

[0028] Referring to FIG. **1**, the semiconductor device **100**R includes a substrate **10**, a barrier layer **12**, a channel layer **14**, an electron supply layer **16**, a cap layer **18**, an insulating film **20**, a source electrode **22**, a drain electrode **24**, a gate electrode **26**, and interlayer insulating films **30** and interconnection lines **32**.

[0029] The barrier layer **12** contacts the upper surface of the substrate **10**, and the channel layer **14** contacts the upper surface of the barrier layer **12**. The electron supply layer **16** contacts the upper layer of the channel layer **14**, and the cap layer **18** contacts the upper surface of the electron supply layer **16**. The insulating film **20** contacts the upper surface of the cap layer **18**. The source electrode **22**, the drain electrode **24** and the gate electrode **26** are formed in openings in the insulating film **20**, and contact the upper surface of the cap layer **18**. The interlayer insulating film **30** contacts the upper layers of the insulating film **20** and the gate electrode **26**. Interconnection lines **32** are formed in openings in the interlayer insulating film **30**, and contact the upper surface of the source electrode **22** or that of the drain electrode **24**.

[0030] The substrate **10** is formed of, for example, silicon carbide (SiC) or sapphire. The semiconductor layers (the barrier layer **12**, channel layer **14**, electron supply layer **16** and cap layer **18**) are nitride semiconductor layers. The barrier layer **12** is made of, for example, aluminum nitride (AlN). The channel layer **14** and the cap layer **18** are made of, for example, gallium nitride (GaN). The electron supply layer **16** is made of, for example, aluminum gallium nitride (AlGaN).

The insulating film **20** and the interlayer insulating film **30** are made of, for example, silicon nitride (SiN). The source electrode **22** and the drain electrode **24** are made of a metal, each of which may be composed of, for example, a titanium (Ti) layer and an aluminum (Al) layer stacked in this order from the cap layer **18**. The gate electrode **26** is made of a metal and may be composed of a nickel (Ni) layer **26***a* and a gold (Au) layer **26***b* stacked in this order from the cap layer **18**. When the drain electrode **24** is set at a positive potential and the gate electrode **26** is set at a negative potential with the source electrode **22** being grounded, a two-dimensional electron gas (2DEG) is generated in the channel layer **14**. And electrons in 2DEG move between the source and the drain.

[0031] A description is now given of a problem that occurs in the comparative example. FIG. **2**A is a schematic view that illustrates an example in which the insulating film has a large Si composition ratio. In FIG. **2**A, a portion in the vicinity of the gate electrode **26** is enlarged and hatching is omitted.

[0032] Referring to FIG. **2**A, a denatured layer including gallium oxide (Ga:O in FIG. **2**A) is formed on the upper surface of the cap layer **18**, and dots show electrons. In order to remove the denatured layer, the composition ratio of Si to N (nitrogen) in the insulating film **20** is made larger than a Si/N ratio of 0.75 of silicon nitride (Si_3N_4) having the stoichiometric composition. Silicon in the insulating film **20** has an anti-bonding orbital (the dot on the right side of each Si in FIG. **2**A) in which Si is not bonded to N, and many silicon-hydrogen (Si—H) bonds are formed. As depicted by arrows in FIG. **2**A, the denatured layer is removed in such a manner that oxygen ions (O ions) in the cap layer **18** are bonded to the anti-bonding orbitals of Si in the insulating film **20**. However, Si in the insulating films functions as an electron trap, and traps an electron in 2DEG.

[0033] FIG. **2**B is a schematic diagram that illustrates an exemplary band diagram. The horizontal axis denotes the depth of the semiconductor device **100**R, and the vertical axis denotes energy. A reference Ef is the Fermi energy, Ec is the energy of the bottom of the conduction band, and Ev is the energy of the top of the valence band. Solid lines denote energy before the electrons are trapped, and broken lines denote energy after the electrons are trapped. As indicated by arrows in FIG. **2**B, the electrons in 2DEG are captured in the electron traps in the insulating film **20**, and the energy band of the insulating film **20** shifts to the minus side. Accordingly, the energy bands of the channel layer **14**, the electron supply layer **16** and the cap layers **18** shift to the minus side. Since the energy Ec of the conduction band of the channel layer **14** shifts to the minus side, the number of electrons in 2DEG decreases. Thus, the saturation current of the semiconductor device **100**R decreases.

[0034] Next, a description is given of an exemplary structure in which the insulating film **20** has a stoichiometric composition (Si_3N_4). FIG. **3** is a schematic diagram of such an exemplary structure. As illustrated in FIG. **3**, since the Si/N ratio is 0.75, the Si atoms in the insulating film **20** do not have anti-bonding orbitals. Thus, the Si atoms have a difficulty in trapping the electrons in 2DEG. Since the trapping of electrons is limited, the shift of the energy band is limited. However, Si in the insulating film **20** has a difficulty in bonding with O ions. Thus, Ga:O in the cap layer **18** remains. As illustrated by arrows, O ions move due to the application of voltages to the source electrode **22**, the drain electrode **24** and the gate electrode **26** or temperature variation. The above movement of O ions varies the capacitance of the semiconductor device **100**R, which may be the gate-source capacitance or the gate-drain capacitance. For example, a variable capacitance Cv is formed between the gate electrode **26** and the channel, layer **14** is generated, and varies. This variation causes a drift in the gain of the semiconductor device **100**R. Such a gain drift may occur even in a case where the composition of the insulating film **20** is not stoichiometric strictly, but is close to the stoichiometric composition. As described above, the comparative example has difficulty in suppressing both the capacitance variation and the current variation.

First Embodiment

[0035] A first embodiment has an exemplary structure having a film having a comparatively high composition ratio of Si to N, and a stoichiometric film provided on the large composition film. FIG. **4**A is a cross-sectional view of a semiconductor device in accordance with the first embodiment.

[0036] Referring to FIG. **4**A, the semiconductor device **100** is configured to have a first film **34** provided on the cap layer **18** and a second film **36** provided on the first film **34**. The first film **34** contacts the upper surface of the cap layer **18**. The second film **36** contacts the upper surface of the first film **34**. The first film **34** and the second film **36** may be made of SiN. The Si/N ratio of the first film **34** is larger than 0.75. The second film **36** has the stoichiometric composition. The first film **34** has an exemplary thickness that is equal to or larger than 1 nm and is equal to or smaller than 5 nm. The second film **36** has an exemplary thickness that is equal to or larger than 20 nm and is equal to or smaller than 100 nm.

[0037] FIG. **4**B is a diagram that schematically illustrates an enlarged view of the gate electrode **26** and its vicinity. Since the Si/N ratio of the first film **34** is larger than 0.75, Si atoms in the first film **34** have anti-bonding orbitals. The anti-bonding orbitals of Si and the O ions in the cap layer **18** are bonded, so that the denatured layer is removed. Thus, it is possible to suppress variation in the capacitance of the semiconductor device **100** due to the movement of the O ions. Since the second film **36** has the stoichiometric composition, the electron traps are hard to be formed in the second film **36**. Thus, the trapping of the electrons in 2DEG is suppressed and variation in the saturation current is also suppressed. As described above, the use of stacked layers having different Si composition ratios realize the suppression of both the current variation and the capacitance variation.

Table 1 shows the standard Gibbs energies of formation of some substances (hereinafter simply referred to as Gibbs energy).

TABLE 1

Substance	In_2O_3	Ga_2O_3	Al_2O_3	SiO_2
Gibbs energy (kJ/mol)	−419.4	−499	−791	−857

As shown in Table 1, the Gibbs energy decreases in the order of indium oxide (In_2O_3), gallium oxide (Ga_2O_3), aluminum oxide (Al_2O_3) and silicon oxide (SiO_2). As the Gibbs energy is lower, the substance is more stable. The Gibbs energy of Ga_2O_3 formed in the denatured layer is −499 kJ/mol. As illustrated in FIG. **4**B, the Si atoms in the first film **34** are bonded to the O ions, and SiO_2 is thus generated. The Gibbs energy of SiO_2 is −857 kJ/mol, and is lower than the Gibbs energy of Ga_2O_3. Since the first film **34** and the cap layer **18**

contact each other, the reaction of the Si atoms and the O ions proceeds spontaneously, and the denatured layer is effectively removed. In an exemplary case where the cap layer **18** includes indium (In), the denatured layer includes In_2O_3. Since the Gibbs energy of SiO_2 is lower than that of In_2O_3, the denatured layer is effectively removed. A case of Al and Al_2O_3 will be described later.

[0038] A description is now given of a fabrication method of the semiconductor device **100**. FIGS. **5**A through **5**C and FIGS. **6**A through **6**C are cross-sectional views that illustrate an exemplary method for fabricating the semiconductor device **100**.

[0039] Referring to FIG. **5**A, the barrier layer **12**, the channel layer **14**, the electron supply layer **16** and the cap layer **18** are grown by, for example, MOCVD (Metal. Oxide Chemical Vapor Deposition). Referring to FIG. **5**B, the source electrode **22** and the drain electrode **24** are provided on the cap layer **18** by, for example, an evaporation process and a liftoff process. Referring to FIG. **5**C, the first film **34** and the second film **36** are provided by, an ALD (Atomic Layer Deposition) method.

[0040] Referring to FIG. **6**A, an opening is formed in the first film **34** and the second film **36**, and the gate electrode **26** is provided in the opening by sputtering, for example. Referring to FIG. **6**B, the interlayer insulating film **30** is formed on the gate electrode **26**, the first film **34** and the second film **36**. Referring to FIG. **6**C, openings are formed in the interlayer insulating film **30**, and the interconnection lines **32** are provided in the openings by plating. The structure of the semiconductor device **100** illustrated in FIG. **6**C is complete.

[0041] A description is now given of conditions for growing the first film **34** and the second films **36**. The ALD method forms films as follows. A first source gas is supplied in an ALD apparatus, and a single-atom-thick layer of Si is formed. Then, the first source gas is exhausted from the ALD apparatus. A second source gas is supplied to the ALD apparatus, and the Si layer is converted into nitride. Then, the second source gas is exhausted from the ALD apparatus. A supply time is defined as the time during which the first source gas is supplied. A first exhaust time is defined as the time during which the first source gas is exhausted. The nitridization time is defined as the time during which the second source gas is supplied. A second exhaust time is defined as the time during which the second source gas is exhausted. One cycle is defined as the time from the initiation of supply of the first source gas to the completion of exhaust of the second source gas.

[0042] FIGS. **7**A, **7**B, **8**A, **8**B, **9**A and **9**B are diagrams that show exemplary conditions for growing the first film **34** and the second film **36** made of SiN. In the conditions for growing the films shown in FIGS. **7**A through **9**B, the first source gas includes BTBAS (Bis(tertiary-butyl-amino)silane: $CH_4H_4NH_2)SiH_2$), TDMAS (Tris(dimethylamino)silane: $SiH(N(CH_2)_2)_3$), DMS (dimethyl silane: $(CH_3)_2SiH_2$), BEMAS (Bis(ethyl-methyl-amino)silane: $CH_3(C_2H_5)N)_2SiH_2$), $SiCl_4$ and Si_2Cl_2, respectively. The second source gas is common to the conditions shown in FIGS. **7**A through **9**B, and includes ammonia (NH_3) plasma or N_2 plasma. As described above, the first film **34** and the second film **36** may be grown by aminosilane (general expression: $(R1R2N)_nSi_{4-n}$).

[0043] By changing the first supply time and the second supply time, it is possible to grow, from the same source gas, the first film **34** and the second film **36** having different compositions. The number of cycles may be changed in accordance with the thickness of the first film **34** and that of the second film **36**. The film growing temperature (the temperature in the ALD apparatus) may be equal to or higher than 200° C. and may be equal to or lower than 400° C., for example. Any of the film growing conditions illustrated in FIGS. **7**A through **9**B may be used or yet another condition may be used.

[0044] A description is now given of the reason why the first film **34** is formed by the ALD method. When the first film **34** is too thick, many electron traps are formed since a large number of Si atoms having anti-bonding orbitals exists in the first film **34**. Thus, electros in 2DEG may be captured in the electron traps. In contrast, when the first film **34** is too thin, the removal of the denatured layer has a difficulty because a small number of Si atoms having anti-bonding orbitals exists. In order to suppress the trapping of electrons and remove the denatured layer, the thickness of the first film **34** has a thickness equal to or larger than 1 nm and equal to or smaller than 5 nm, and may be not smaller than 1.5 nm or 2 nm and may be not larger than 4.5 nm or 4 nm. As described above, the first film **34** is required to be reliably formed so that the first film **34** is thin and is even or almost even in thickness. This requirement may be preferably achieved by the ALD method. Although the first film **34** may be formed by plasma CVD, there is a difficulty in reliably forming a film thickness of not larger than 5 nm, which corresponds to a three- or four-atom-thick layer and in removing the denatured layer efficiently, as compared with the ALD method. Another method besides the ALD method may be used as long as the first film **34** is formed so as to be thin and even or almost even in thickness. The composition ratio of Si to N in the first film **34** is larger than 0.75, and may be 0.78, 0.8, 0.85 or 0.9.

[0045] The second film **36** may be formed to have the substantive stoichiometric composition. The substantive stoichiometric composition includes not only the strict stoichiometric composition but also a composition including an impurity having a difficulty in removal in the fabrication process. For example, the second film **36** may be formed by sputtering. However, in order to make the composition of the second film **36** closer to the stoichiometric value, the second film **36** is preferably formed by the ALD method. The second film **36** is preferably equal to or larger than 20 nm and is equal to or smaller than 100 nm in order to make it difficult for the electron traps to be formed and to protect the semiconductor layer from moisture. For example, the thickness of the second film **36** may be not smaller than 25 nm or 30 nm and not larger than 95 nm or 90 nm.

[0046] The second film **36** has the following effects other than those described above. In a case where the gate electrode **26** is formed in an opening in the first film on the cap layer **18**, a parasitic capacitance between the gate electrode **26** and the cap layer **18** is concerned because the first film **34** is thin. With the above in mind, the gate electrode **26** is formed in the opening in the first film **34** and the second film **36** on the cap layer **18** in order to increase the distance between the gate electrode **26** and the cap layer **18** and to reduce the parasitic capacitance. However, it is not essential to form the second film **36** on the first film **34**, but the second film **36** may be omitted.

Second Embodiment

[0047] A second embodiment has an exemplary structure in which the first film **34** is made of Al. A cross-sectional view of a semiconductor device **200** in accordance with the second

embodiment is the same as that of the semiconductor device **100**. FIG. **10**A is a schematic diagram illustrating an enlarged view of the gate electrode **26** of the semiconductor device **200** and its vicinity.

[0048] Referring to FIG. **10**A, the Al atoms in the first film **34** are bonded to the O ions in the cap layer **18**. Thus, as in the case of the first embodiment, the denatured layer is removed and the trapping of electros is suppressed. The thickness of the first film **34** may be equal to that used in the first embodiment. The semiconductor device **200** may be fabricated as follows. An illustration of the fabrication method of the semiconductor device **200** is omitted, and FIGS. **4**A through **5**C are referenced.

[0049] As illustrated in FIG. **4**B, the first film **34** is formed on the cap layer **18** by the ALD method. The second film **36** is formed by the ALD method. The step of forming the first film **34** and the step of forming the second film **36** are successively carried out. For example, the same ALD apparatus may be used to form the first film **34** and the second film **36**. Also, after the first film **34** is formed, the second film **36** is formed without the first film **34** being exposed to atmosphere. The other steps are the same as those of the first embodiment.

[0050] FIG. **10**B illustrates conditions for growing the first film **34** of Al. As illustrated in FIG. **10**B, the source gas includes TMA (trimethylaluminum), for example.

[0051] Al is likely to be oxidized. When the substrate **10** on which the first film **34** has been form is removed from the ALD apparatus and is exposed to atmosphere, an oxide film is formed on the surface of the first film **34**. In order to prevent the oxide film from being formed, it is preferable that the step of forming the first film **34** and that of forming the second film **36** are successively carried out. Since the first film **34** is formed by the ALD apparatus, the first film **34** is thin and even in thickness. Thus, the denatured layer is effectively removed.

[0052] The Al atoms and O ions are bonded to generate Al_2O_3. As previously shown in Table 1, the Gibbs energy of Al_2O_3 is −791 kJ/mol, and is lower than that of Ga_2O_3. Thus, the reaction of the Al atoms and the O ions proceeds, and the denatured layer is effectively removed. Since the Gibbs energy of Al_2O_3 is lower than that of In_2O_3, the denatured layer is effectively removed even in an exemplary case where the gap layer **18** includes In. Since the Gibbs energy of Al_2O_3 is higher than that of SiO_2, Al is hard to be bonded to the ions as compared with Si. Therefore, Al is solely arranged to contact the cap layer **18** like the first film **34**, so that the bonding of the Al atoms and the O ions can proceed and the denatured layer can be removed.

[0053] In the first and second embodiments, the second film **36** may be formed of an insulative substance having a stoichiometric composition other than Si_3N_4. The second film **36** may include at least one of SiO_2, Al_2O_3 and AlN, for example. The first film **34** may be formed of a substance other than SiN and Al, and the second film **36** may be formed of a substance other than Si_3N_4.

[0054] An exemplary case using silicon oxide is now described. The composition of the second film **36** is a stoichiometric composition (for example, SiO_2). The composition ratio of Si to O in the second film **36** is 0.5. The Si/O ratio in the first film **34** is larger than 0.5. As shown in Table 1, the Gibbs energy of SiO_2 is low. Thus, the arrangement of the first film **34** and the cap layer **18** which contact each other facilitates the bonding of the Si atoms and the O ions in the first film **34**. Therefore, the denatured layer is removal.

[0055] FIGS. **11** through **16** illustrate conditions for growing the first film **34** formed by silicon oxide (for example, Si-rich Si_2O_3) and the second film **36** formed by silicon oxide. The first source gases used in the conditions for growing the films in FIGS. **11** through **14** include BTBAS, TDMAS, DMS and BEMAS, respectively, and the second source gases include oxygen (O_2), plasma, ozone (O_3), water (H_2O) and a Lewis base. The Lewis base is a complex of the H_2O coordination of pyridine (C_5H_5N). In the conditions illustrated in FIG. **15**, the first source gas includes $SiCl_4$, and the second source gas O_2 plasma or O_3. In the conditions in FIG. **16**, the first source gas includes Si_2Cl_6, and the second source gas includes O_2 plasma or O_3. As shown in FIGS. **11** through **16**, it is preferable that the oxidization time is changed in accordance with the type of the second source gas.

[0056] Another exemplary case using aluminum oxide is now described. The composition of the second film **36** has the stoichiometric composition (Al_2O_3). The composition ratio of Al to O in the second film **36** is 0.67.

[0057] FIG. **17** shows conditions for growing the first film **34** of aluminum and the second film **36** of aluminum oxide. As shown in FIG. **17**, the first source gas includes TMA, and the second source gas includes O_2 plasma, O_3, H_2O or Lewis base.

[0058] Yet another exemplary case is now described. The second film **36** has the stoichiometric composition (AlN). The composition ratio of Al to N in the second film **36** is 1.

[0059] FIG. **18** shows conditions for growing the first film **34** of aluminum and the second film **36** of aluminum nitride. As shown in FIG. **18**, the first source gas includes TMA, and the second source gas includes NH_3 plasma or N_2 plasma. The film growing conditions in FIGS. **11** through **18** include conditions for temperature that range from 200° C. to 400° C., for example.

[0060] The barrier layer **12**, the channel layer **14**, the electron supply layer **16** and the cap layer **18** may be made of nitride semiconductors other than the above-described semiconductors. The nitride semiconductors are semiconductors including N, and may be indium gallium nitride (InGaN), indium nitride (InN) and aluminum indium gallium nitride (AlInGaN) other than the above-described semiconductors.

[0061] The present invention is not limited to the specifically described embodiments, but may include other embodiments and variations without departing from the scope of the present invention.

What is claimed is:

1. A method for fabricating a semiconductor device comprising:

forming a first film that contact a surface of the nitride semiconductor layer and have a thickness equal to or larger than 1 nm and equal to or smaller than 5 nm, the first film being made of silicon nitride having a composition ratio of silicon to nitrogen larger than 0.75, silicon oxide having a composition ratio of silicon to oxygen larger than 0.5, or aluminum; and

forming a source electrode, a gate electrode and a drain electrode on the nitride semiconductor layer.

2. The method according to claim **1**, further comprising forming a second film that contacts a surface of the first film, wherein the second film is substantially a stoichiometric composition and is made of one of silicon nitride, silicon oxide, aluminum oxide and aluminum nitride.

3. The method according to claim **1**, wherein the first film is silicon nitride, and the method further comprises forming

of a second film composed of silicon nitride having a silicon composition smaller than the first film.

4. The method according to claim **2**, wherein a formation method of the first film is an atomic layer deposition method, and a formation method of the second film is an atomic layer deposition method.

5. The method according to claim **3**, wherein a formation method of the first film is an atomic layer deposition method, and a formation method of the second film is an atomic layer deposition method.

6. The method according to claim **2**, wherein the second film has a thickness that is equal to or larger than 20 nm and is equal to or smaller than 100 nm.

7. The method according to claim **3**, wherein the second film has a thickness that is equal to or larger than 20 nm and is equal to or smaller than 100 nm.

8. The method according to claim **1**, wherein the first film is composed of aluminum, and the method comprises forming a second film on the first film, a formation of the second film is performed in-situ after a formation of the first film.

9. The method according to claim **8**, wherein the formation of the first and second film is performed under an atomic layer deposition apparatus.

10. The method according to claim **1**, wherein the first film is formed between the source electrode and the gate electrode, and is between the gate electrode and the drain electrode.

11. The method according to claim **1**, wherein the first film is composed of silicon nitride, and the composition ratio of silicon to nitrogen of first film is larger than 0.8.

12. The method according to claim **1**, wherein the first film is composed of silicon nitride, and the composition ratio of silicon to nitrogen of first film is larger than 0.85.

13. The method according to claim **1**, wherein the first film is composed of silicon nitride, and the composition ratio of silicon to nitrogen of first film is larger than 0.9.

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