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METHOD FOR FORMING REFRACTORY METAL-SILICON-NITROGEN CAPACITORS AND STRUCTURES FORMED

Field of the Invention

The present invention generally relates to a method for fabricating semiconductor devices incorporating capacitor elements formed of refractory metal-silicon-nitrogen and devices formed and more particularly, relates to a method for fabricating semiconductor devices that incorporates capacitor elements formed by depositing multi-layers of refractory metal-silicon-nitrogen in the same process chamber by varying processing conditions and devices formed by such fabrication.

Background of the Invention

In semiconductor fabrication, capacitors are frequently formed in-situ in a semiconductor structure. For instance, an in-situ formed capacitor can be found in a dynamic random access memory device. The process required for forming

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the capacitor is complicated. It involves the deposition of different layers of materials by different chemical processes, and most likely, in different process chambers. For instance, layers deposited of a polysilicon material are frequently used as the electrode, while layers deposited of an insulating material such as silicon oxide are frequently used as the capacitor dielectric. The process therefore requires multiple number of depositions, from multiple number of different materials conducted in multiple number of process chambers for the forming and patterning of the capacitor.

004 In modern semiconductor devices, refractory metals have been frequently used in semiconductor processes to form vias or contacts. However, refractory metal-nitrogen alloys have not been used widely in the processing of semiconductor devices. For instance, only recently, U.S. Patent No. 5,892,281 describes the use of tantalum-aluminum-nitrogen alloys in semiconductor devices as a diffusion barrier and an adhesion promoter. The patent discloses the use of Ta-Al-N in a semiconductor device to prevent inter-diffusion between surrounding layers, for instance, between two conductor layers; between a semiconductor layer and a conductor layer; between an insulator layer and a conductor layer; between an insulator layer and a semiconductor layer; or between two semiconductor

Layers. A second use of Ta-Al-N is to promote adhesion with adjacent layers, for instance, between two conductor layers; between a conductor layer and an insulator layer; between a semiconductor layer and a conductor layer; or between two semiconductor layers. However, U.S. Pat. No. 5,892,281 does not teach any other uses for tantalum-aluminum-nitrogen alloys in semiconductor fabrication.

Summary of the Invention

In accordance with the present invention, a method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure and the structure formed are disclosed.

It is therefore a first aspect of the present invention to provide a method for forming a capacitor in-situ in a semiconductor structure that at least mitigates the drawbacks or the shortcomings of the conventional methods.

It is another aspect of the present invention to provide a method for forming a capacitor in-situ in a semiconductor structure that requires only the deposition of a single material.

It is a further aspect of the present invention to provide a method for forming a capacitor in-situ in a semiconductor structure that requires only the deposition of a single material of refractory metal-silicon-nitrogen in multiple layers.

It is another further aspect of the present invention to provide a method for forming a capacitor in a semiconductor structure that requires only the deposition of a single material of TaSiN in multiple layers under different processing conditions.

It is still another aspect of the present invention to provide a method for forming a capacitor in a semiconductor structure by depositing multiple layers of a refractory metal-silicon-nitrogen each having a different stoichiometry.

It is yet another aspect of the present invention to provide a method for forming a capacitor in-situ in a semiconductor structure by depositing multiple layers of a refractory metal-silicon-nitrogen each having a different sheet resistance value.

It is still another further aspect of the present invention to provide a method for forming a capacitor in a semiconductor structure by depositing multiple layers of refractory metal-silicon-nitrogen in the same chamber by varying a flow rate of partial pressure of nitrogen into the chamber.

It is yet another further aspect of the present invention to provide a semiconductor capacitor structure which has a lower electrode, a middle dielectric layer and an upper electrode formed of the same refractory metal-silicon-nitrogen material but with different stoichiometry.

In a preferred embodiment, a method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure can be carried out by the operating steps of positioning a preprocessed semiconductor substrate in a sputtering chamber; flowing Ar gas into the sputtering chamber; sputter depositing a first refractory metal-silicon-nitrogen layer on the substrate from a refractory metal silicide target, or from targets of a refractory metal and a silicon; flowing N_2 gas into the sputtering chamber such that concentration of the N_2 gas in the chamber is at least 35% by adjusting the flow rate or partial pressure of N_2; sputter depositing a second refractory metal-silicon-nitrogen layer on top of the first refractory metal-silicon-nitrogen layer; stopping the N_2 gas

flow into the sputtering chamber; sputter depositing a third refractory metal-silicon-nitrogen layer on top of the second refractory metal-silicon-nitrogen layer; and photolithographically forming the first, second and third refractory metal-silicon-nitrogen layers into a capacitor.

0015 The method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure may further include the step of in-situ annealing the capacitor at a temperature of at least 80°C, or the step of flowing Ar gas into the sputtering chamber at a flow rate between about 10 sccm and about 200 sccm, or the step of flowing N_2 gas into the sputtering chamber at a flow rate between about 1 sccm and about 100 sccm. The method may further include the step of sputter depositing the first and the third refractory metal-silicon-nitrogen layer to a thickness between about 100 Å and about 5000 Å, or the step of depositing the second refractory metal-silicon-nitrogen layer to a thickness between about 100 Å and about 5000 Å. The method may further include the step of sputter depositing the first and the third refractory metal-silicon-nitrogen layer each having a sheet resistance of not higher than 50 ohm/sq., or the step of sputter depositing the second refractory metal-silicon-nitrogen layer which has a dielectric constant greater than 7.5. The method

may further include the step of sputter depositing the first, second and third refractory metal-silicon-nitrogen layer formed of a refractory metal selected from the group consisting of Ta, Nb, V, W and Ti.

0016 The present invention is further directed to a semiconductor capacitor structure which includes a lower electrode formed of a first refractory metal-silicon-nitrogen material that has a sheet resistance not higher than 50 ohm/sq; a middle dielectric layer formed of a second refractory metal-silicon- nitrogen material that has a dielectric constant greater than 7.5; and an upper electrode formed of the first refractory metal- silicon-nitrogen material.

0017 In the semiconductor structure of a capacitor, each of the lower electrode and upper electrode is formed to a thickness between about 100 Å and about 5000 Å, the middle dielectric layer is formed to a thickness between about 100 Å and about 5000 Å. The refractory metal in the first, second and third refractory metal-silicon-nitrogen material is selected from the group consisting of Ta, Nb, V, W and Ti. The first refractory metal- silicon-nitrogen material has a sheet resistance of not higher than 50 ohm/sq., while the second refractory

metal-silicon- nitrogen material has a dielectric constant greater than 7.5

BRIEF DESCRIPTION OF THE DRAWINGS

0018 These and other objects, features and advantages of the present invention will become apparent from the following detailed description and the appended drawings in which:

0019 Figure 1 is an enlarged, cross-sectional view of a semiconductor structure that includes the present invention capacitor formed of three layers of a refractory metal-silicon-nitrogen material.

0020 Figure 2 is a graph illustrating data obtained in deposition system #1 showing the dependence of the sheet resistance of the present invention refractory metal-silicon-nitrogen material on the nitrogen content by adjusting nitrogen gas.

0021 Figure 3 is a graph illustrating data obtained in deposition system #1 showing the dependence of the film uniformity of the present invention refractory metal-silicon-nitrogen material on the nitrogen content by adjusting nitrogen flow.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

0022 The present invention discloses a method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure by the in-situ forming of multiple refractory metal-silicon-nitrogen layers each having a different stoichiometry on a semiconductor substrate and then, photolithographically forming the multiple layers into a capacitor.

0023 In the method, a preprocessed semiconductor substrate is first positioned in a sputtering chamber, Ar gas is then flown into the sputtering chamber to sputter deposit a first refractory metal-silicon-nitrogen layer on the substrate from either a single refractory metal silicide target or from two targets of a refractory metal and silicon. N_2 gas is then flown into the sputtering chamber until the concentration of the N_2 gas in the chamber reaches at least 35 % by volume by adjusting the flow or partial pressure of N_2, a second refractory metal-silicon-nitrogen layer is then sputter deposited on top of the first refractory metal-silicon-nitrogen layer. The N_2 gas flow is then stopped to deposit a third refractory metal-silicon-nitrogen layer on top of the second refractory metal-silicon-nitrogen layer. After the deposition of all three refractory metal-silicon-nitrogen layers, the layers are photolithographically formed into a capacitor.

0024 The present invention novel method may be followed by an optional annealing step, wherein the capacitor structure is in- situ annealed at a temperature of at least 80°C, and preferably at a temperature of at least 100°C. In the preferred embodiment, the Ar gas flows into the sputtering chamber at a flow rate between about 10 sccm and about 200 sccm. The N_2 gas flows into the sputtering chamber during the formation of the middle refractory metal-silicon-nitrogen layer of high sheet resistance at a flow rate between about 1 sccm and about 100 sccm.

0025 The invention further discloses a semiconductor structure of a capacitor that is constructed by a lower electrode, a middle dielectric layer and an upper electrode. The lower electrode and the upper electrode are both formed of a first refractory metal-silicon-nitrogen material that has a sheet resistance not higher than 50 ohm/sq., while the middle dielectric layer is formed of a second refractory metal-silicon-nitrogen material that has a dielectric constant greater than 7.5. Each of the lower and upper electrodes and the middle dielectric layer is formed to a thickness between about 100 Å and about 5000 Å. The refractory metal in the first, the second and the third refractory

metal-silicon-nitrogen materials may be selected from the group consisting of Ta, Nb, V, W and Ti.

0026 Referring initially to Figure 1, wherein an enlarged, cross-sectional view of the present invention CMOS structure 10 with a capacitor stack 20 and an insulating material layer 12 formed on top is shown. A lower electrode layer 14, a dielectric layer 16 and an upper electrode layer 18 are deposited of refractory metal-silicon-nitrogen materials that have different stoichiometry and patterned over the diffusion barrier 22. The insulating material layer 12 is deposited over the entire wafer and contact openings 24,26 and 28 are etched which are latter filled with a conductive material for forming electrical contacts to the diffusion barrier 22, the fuse 30 and the resistor 32, respectively. In the particular structure 10, shown in Figure 1, the diffusion barrier 22 prevents reaction between the lower electrode 14 and the polysilicon contact via 34. The fuse 30 can be blown by forcing a large current through the line-fuse material-via structure causing excessive heating and melting in the fuse material and thus, loss of electrical conductivity.

0027 A refractory metal-silicon-nitrogen material such as TaSiN has wide range of electrical resistivities depending on

the stoichiometry of the TaSiN film. For instance, under normal DC sputtering conditions, films ranging from 0.2 ohm-cm to nearly 10^6 ohm-cm can be obtained by varying the nitrogen to argon ratio, i.e. from 4 vol. % to 50 vol. % by adjusting flow rate or partial pressure of nitrogen. At higher nitrogen ratios, the film becomes insulating. The rate of increase in electrical resistance with nitrogen flow is monotonic, but the increases are much steeper at the higher nitrogen flow ratios.

0028 Table 1 shows data on the relationship between the sheet resistance of TaSiN films and the nitrogen percentage in the argon sputtering plasma. The materials listed in Table 1 were deposited in deposition system #1 by adjusting the flow of N_2 into the Ar sputtering plasma. The forty-nine point resistance measurement indicates that film non-uniformity increases as sheet resistance increases with greater amounts of nitrogen in the sputtering plasma. For example, a significant uniformity degradation occurs when nitrogen content increases from 40 to 44, which is accompanied by a sheet resistance increases of an order of magnitude.

Table 1

N_2 in Ar Sputtering Plasma (vol. %)	Rs (Ohm/sq)	Uniformity (49 points, %)
4	25.78	4.4
7	28.6	4.7
10	35.6	4.9
13	43.3	4.9
16	52.91	4.7
20	71.52	4.5
24	100.73	4.3
28	151.47	4.4
32	255.5	5.8
36	528.3	9.2
40	1727	17.2
44	14663	29.8
48	657770	44.3

0029 Tables 2 and 3 show electrical properties for two TaSiN compositions which are insulators and can be used as a dielectric for a capacitor application. The materials listed in Tables 2 and 3 were deposited in deposition system #2 by adjusting the partial pressure of N_2 into the Ar sputtering plasma. The capacitance, dissipation factor and dielectric constant are shown as a function of applied frequency. For both films, the dissipation factor increased with increasing frequency whereas the dielectric constant is slightly lower at higher frequencies primarily due to the higher loss (dissipation factor). The error in the measurements is within ± 10%.

Table 2

75.5 nm Ta:Si:N 7.7:30.7:61.6 (50% N_2 in Ar)

Frequency (hz)	Capacitance (pF)	Dissipation Factor	Dielectric Constant
10 k	249 pF	0.020	9.5
40 k	242 pF	0.021	9.2
100 k	238 pF	0.029	9.1

Table 3

58.7 nm Ta:Si:N 9.8:30.2:59.9 (30% N_2 in Ar)

Frequency (hz)	Capacitance (pF)	Dissipation Factor	Dielectric Constant
10 k	282 pF	0.010	8.4
40 k	274 pF	0.034	8.1
100 k	267 pF	0.050	7.9

0030 As shown in Tables 2 and 3, the first sample in Table 2 has a composition of Ta:Si:N of 7.7:30.7:61.5 and was prepared with 50 vol. % nitrogen in Ar plasma. The second sample shown in Table 3 has a composition of 9.8:30.2:59.9 and was prepared with 30% nitrogen in Ar plasma. The dielectric constant for the materials is shown as a function of frequency by using a C-V measurement technique. The dielectric constant decreases slightly with frequency due to the increase in the dissipation factor. The dielectric constant of the present invention TaSiN is between about 8.0 and about 9.5.

0031 Referring now to Figure 2, wherein a graph plotted of sheet resistance of the TaSiN films as a function of nitrogen in the sputtering plasma is shown. Figure 3 shows a graph plotted of resistance uniformity also as a function of nitrogen in the sputtering plasma. The uniformity degrades with higher percentages of N_2 in the Ar sputtering plasma.

0032 The present invention novel method uses a multi-layer structure of TaSiN, each with a different composition to achieve a final material resistance. By utilizing the novel method, the process window for the fabrication process can be greatly increased. For example, it is possible to obtain sheet resistance values between 15 K-ohm/square to insulate with a better uniformity control.

0033 Another benefit made possible by the present invention novel method is the possibility for depositing multi-layer films in-situ to fabricate a capacitor. For example, first deposit a low sheet resistance film to a predetermined thickness as the bottom electrode, then deposit from the same target but with a higher nitrogen flow to form a dielectric film, and finally deposit the third low sheet resistance film as the top electrode. The present invention novel method may optionally include an in- situ annealing step such that the sandwiched film

is ready for capacitor patterning. This allows a reduction in the fabrication cost and therefore, made the present invention method not only suitable for semiconductor front-end applications, such as integration with devices, but also suitable for implementing high- density capacitors at the packaging level.

0034 The present invention novel capacitor may be formed by a refractory metal-silicon-nitrogen material such as TaSiN. The

refractory metal may also be selected from the group of elements consisting of Nb, V, W and Ti. In a typical refractory metal-silicon-nitrogen composition of TaSiN, the composition may contain between about 5 at. % and about 55 at. % Ta, between about 10 at. % and about 45 at. % Si, and between about 30 at. % and about 80 at. % N. The semiconductor structure wherein the capacitor is formed may also include a conductive element used to establish electrical connection with the capacitor. The conductive element may be formed of doped polysilicon, metal silicide, polycide, refractory metal, aluminum, copper and alloys thereof.

0035 The refractory metal-silicon-nitrogen films, such as TaSiN, have the advantage of being either insulating or

resistive depending on the ratio of refractory metal to the silicon to the nitrogen. The films are thermally stable to annealing at temperature up to 800°C.

0036 The present invention novel method can further be used to fabricate a modulated RC stack structure by modulating the mixture of nitrogen to argon during a sputtering deposition process.

0037 The present invention novel method for forming refractory metal-silicon-nitrogen capacitors and the structures formed have therefore been amply described in the above description and in the appended drawings of Figures 1-3.

0038 While the present invention has been described in an illustrative manner, it should be understood that the terminology used is intended to be in a nature of words of description rather than of limitation.

0039 Furthermore, while the present invention has been described in terms of a preferred embodiment, it is to be appreciated that those skilled in the art will readily apply these teachings to other possible variations of the inventions.

0040 The embodiment of the invention in which an exclusive property or privilege is claimed are defined as follows.

What Is Claimed Is:

1. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure comprising the steps of:

positioning a preprocessed semiconductor substrate in a sputtering chamber;

flowing Ar gas into said sputtering chamber;

sputter depositing a first refractory metal-silicon nitrogen layer on said substrate;

flowing N_2 gas into said sputtering chamber such that concentration of said N_2 gas in said chamber is at least 35% by adjusting the flow or partial pressure of N_2 ;

sputter depositing a second refractory metal-silicon-nitrogen layer on top of said first refractory metal-silicon nitrogen layer;

stopping said N_2 gas flow into said sputter chamber;

sputter depositing a third refractory metal-silicon-nitrogen layer on top of said second refractory metal-silicon-nitrogen layer; and

photolithographically forming said first, second and third refractory metal-silicon-nitrogen layers into a capacitor.

2. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of in-situ annealing said capacitor at a temperature of at least 80°C.

3. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of flowing said Ar gas into said sputter chamber at a flow rate between about 10 sccm and about 200 sccm.

4. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of flowing said N_2 gas into said sputter chamber at a flow rate between about 1 sccm and about 100 sccm.

5. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said first and said third refractory metal-silicon-nitrogen layer to a thickness of between about 100 Å and about 5000 Å.

6. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said second refractory metal-silicon-nitrogen layer to a thickness of between about 100 Å and about 5000 Å.

7. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said first and said third refractory metal-silicon-nitrogen layer each having a sheet resistance of not higher than 50 ohm/sq.

8. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said second refractory metal-silicon-nitrogen layer which has a dielectric constant greater than 7.5

9. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said first, second and third refractory metal-silicon-nitrogen layers formed of a refractory metal selected from the group consisting of Ta, Nb, V, W and Ti.

10. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said first, second and third refractory metal-silicon-nitrogen layers from a sputtering target of refractory metal silicide.

11. A method for forming a refractory metal-silicon-nitrogen capacitor in a semiconductor structure according to claim 1 further comprising the step of sputter depositing said first, second and third refractory metal-silicon-nitrogen layers from two sputtering targets of a refractory metal and a silicon.

12. A semiconductor capacitor structure comprising:

a lower electrode formed of a first refractory metal-silicon-nitrogen material having a sheet resistance not higher than 50 ohm/sq;

a middle dielectric layer formed of a second refractory metal-silicon-nitrogen material having a dielectric constant greater than 7.5; and

an upper electrode formed of said first refractory metal-silicon-nitrogen material.

13. A semiconductor structure of a capacitor according to claim 12, wherein each of said lower electrode and upper electrode being formed to a thickness between about 100 Å and about 5000 Å.

14. A semiconductor structure of a capacitor according to claim 12, wherein said middle dielectric layer being formed to a thickness between about 100 Å and about 5000 Å.

15. A semiconductor structure of a capacitor according to claim 12, wherein said refractory metal in said first, second and third refractory metal-silicon-nitrogen material being selected from the group consisting of Ta, Nb, V, W and Ti.

16. A semiconductor structure of a capacitor according to claim 12 wherein said first refractory metal-silicon-nitrogen layer has a sheet resistance of not higher than 50 ohm/sq.

17. A semiconductor structure of a capacitor according to claim 12, wherein said second refractory metal-silicon-nitrogen layer has a dielectric constant greater than 7.5.