High-Performance Metal Hard Mask Process Using Fiber-Textured TiN Film for Cu Interconnects

Naoki Torazawa,a,b Takeshi Harada,a Tatsuya Kabea, Dai Motojima,c and Susumu Matsumotob

a Panasonic Corporation, Kanagawa 224-8539, Japan
b TowerJazz Panasonic Semiconductor Corporation, Toyama 937-8585, Japan
c Panasonic Industrial Devices Engineering Corporation, Toyama 937-8585, Japan

As the wiring pitches in copper (Cu) interconnect continue to become smaller, resistive-capacitive (RC) delay due to the increase in the capacitance between Cu lines becomes a critical problem. Therefore, the low-k value dielectric materials have been studied to reduce the capacitance between Cu lines.1–8 However, the low-k materials are known to be easily damaged by the post-processes such as the resist ashing process with oxygen (O2) plasma.9–11 This is because the alignment pattern for photolithography can be easily recognized through TiN film compared to other metal films such as Tantalum nitride (TaN).20–31 This is because of their low mechanical strength, and it results in k-value increasing.

To suppress the damage of interlayer dielectric by the ashing process during the removal of the trench resist, the metal hard mask (MHM) process has been studied instead of the conventional resist mask process.12–24 As a hard mask in the MHM process, Titanium nitride (TiN) has been investigated.20–30 This is because the alignment pattern for photolithography can be easily recognized through TiN film compared to other metal films such as Tantalum nitride (TaN) film. However, the serious problems occurred in the MHM process due to residual stress in TiN mask. One of the problems is that the trench deformation after the etching process, which is known as the wiggling phenomenon.32 This is due to the stress relaxation of TiN film after the trench formation with the etching process, and it results in the buckled structure. Therefore, the approaches to reduce the residual stress in TiN film used as a hard mask have been also studied. One approach to reduce the residual stress is to reduce the thickness of TiN mask. However, thinner TiN mask tends to result in worse property of a hard mask in the self-aligned via process, and the shrink of the pitches between via and trench occurs. It results in degrading the device yield or the reliability performance of time dependent dielectric breakdown (TDBD).

In this paper, the influence of residual stress in TiN film at a simple L/S pattern and a specific pattern on the MHM process was investigated using a mechanical simulation. To overcome the issue related to Cu void formation, the correlation between the residual stress and the film properties of TiN was investigated, and a potential TiN mask in the MHM process for Cu interconnects is discussed.

Experimental

As a hard mask in the MHM process, TiN film was deposited by the physical vapor deposition (PVD) method using Titanium (Ti) target in a mixture of argon (Ar) and nitrogen (N2). In this test, Cu single damascene structure fabricated with 32 nm node technology was used, and extremely low-k (ELK) film with k-value of 2.4 and Young’s modulus of 8.0 GPa was used as the interlayer dielectric.33,34 The etching process for the MHM process was carried out in chlorine (Cl2)-based plasma.

To investigate the relationship between the residual stress and the feature size of the trench at a simple line and space (L/S) pattern and a specific pattern after the etching process, a mechanical simulation which showed the trench displacement was performed. Cu filling performance was evaluated by observing the surface of the trench after the chemical mechanical polishing (CMP) process with an optical inspection system and a scanning electron microscope (SEM). The feature size of the fine trench was observed with a cross sectional transmission electron microscope (TEM).

The residual stress in TiN film was calculated by Stoney’s equation:35

$$\sigma = \frac{E d^2}{6(1 - \nu) R}$$

where $\sigma$ is residual stress in film, $E$ is substrate Young’s modulus, $\nu$ is substrate Poisson’s ratio, $d$ is film thickness, $R$ is amount of change in the radius curvature. In this evaluation, silicon (Si) substrate Young’s modulus and substrate Poisson’s ratio were 185 GPa and 0.28, respectively.36

The thickness of TiN film as a hard mask for investigating the film property and Cu filling performance was set at 30 nm. The thickness of TiN film was measured with X-ray fluorescence (XRF). The concentration of elements in TiN film was evaluated with X-ray photoelectron spectroscopy (XPS). The crystal orientation of TiN film was investigated using X-ray diffraction (XRD) with characteristic X-ray CuKα radiation. The grain structure was observed using a TEM. The etching performance for TiN in the MHM process was evaluated by observing the surface of TiN film and the feature size of the trench after the etching process with Cl2-based plasma.

Results and Discussion

Influence of residual stress in TiN film on the MHM process.—The relationship between the residual stress in TiN film and the feature size of the trench was investigated using a mechanical simulation. Figure 1 shows the interconnect geometry which was simulated in this test and the result of the mechanical simulation which showed the trench displacement at a L/S pattern and a specific pattern. A L/S pattern was simply consisted of lines and spaces, and a specific...
pattern was that a long trench was surrounded by two short trenches whose length was 500 nm. The residual stress in TiN film used in this simulation was set at compressive stress of 1000 MPa. In this regard, compressive stress was defined as negative by convention. As shown in Figure 1, no displacement was occurred at a simple L/S pattern. On the other hand, the dielectric ridge was found to deform in a direction which decreased the trench width at a specific pattern.

Based on the results of the mechanical simulation, the shape of the trench at a specific pattern was observed with a cross sectional TEM. To prevent the trench deformation due to the shrinking of ELK interlayer dielectric during observing with a TEM, the trench was filled with electroplated Cu and fixed. The results are shown in Figure 2. It was found that the dielectric ridge at the opening of the trench deformed and thus the trench width at the opening narrowed.

The results are consistent with the results of the simulation as shown in Figure 1. This is because the trench at a specific pattern is surrounded by TiN mask which has the high residual compressive stress and the stress in TiN film is released after the trench formation during the etching process. This is known as the wiggling phenomenon in the MIM process.

To investigate the effect of the wiggling on Cu filling performance, the Cu filling of the trench at a specific pattern was evaluated and compared with that at a simple L/S pattern. Figure 3 shows the top view SEM images of the trench at a simple L/S pattern and a specific pattern after Cu electroplating and the CMP process. No voids were observed at a simple L/S pattern. On the other hand, the void which led to the open failure formed inside the trench at a specific pattern. Therefore, it is found that the trench deformation at a specific pattern resulted in Cu voids formation and this is a serious issue in the MIM process for Cu interconnects.

In order to prevent the trench deformation, the amount of change in the trench width as a function of the residual compressive stress was simulated. The results are shown in Figure 4. The simulation parameter for the residual compressive stress was set at 500 MPa, 800 MPa and 1000 MPa. As the residual compressive stress in TiN film decreased, the amount of change in trench width became smaller. This means that the trench deformation can be suppressed by decreasing the residual compressive stress in TiN film.

Properties of TiN film.—To reduce the residual compressive stress in TiN film, suppressing the grain growth during the deposition of TiN film is one of the key approaches. In this regard, it is necessary to keep the etching performance for TiN film not to degrade the device yield or the reliability performance of TDBD. In this test, the grain growth was suppressed by changing the deposition mode and decreasing the energy of sputtered atoms during the deposition of TiN film. Table I shows the normalized PVD parameters of the deposition condition for TiN film. In this regard, it is known that the deposition mode in the PVD method changes depending on a flow rate of reactive gas. If a flow rate of reactive gas such as N₂ is low, the surface of the target is still metal and the metal film is deposited on the substrate. This is so called the metallic mode. On the other hand, if a flow rate of reactive gas is increased beyond a certain critical value, the compound layer formed on the surface of the target and the compound film can be deposited on the substrate. This is so called the poison mode. The condition (A) was for the reference and poison mode in the PVD method mentioned above. TiN (A) film was deposited with the condition (A). The tests shown in Figures 2 and 3 were performed using TiN (A) film as a mask. The condition (B) was controlled for the change of the deposition mode. N₂ flow in the condition (B) was low as compared with that in the condition (A) and the ratio of N₂

Table I. Normalized PVD parameters of deposition condition for TiN film.

| Condition / Film | Target power | N₂ flow | T/S |
|------------------|--------------|---------|-----|
| Condition (A) / TiN (A) | 1 | 1 | 1 |
| Condition (B) / TiN (B) | 1 | 0.67 | 1 |
| Condition (C) / TiN (C) | 0.15 | 1.67 | 1.15 |
flow in the condition (B) to that in the condition (A) was set at 0.67. Therefore, the condition (B) resulted in metallic mode. The condition (C) was controlled for the decrease in the energy of sputtered atoms. The target power in the condition (C) was low and the ratio of target power in the condition (C) to that in the condition (A) was set at 0.15. Also, N2 flow in the condition (C) was high and the ratio of N2 flow in the condition (C) to that in the condition (A) was set at 1.7. The gas pressure in the process chamber was increased with the increase of N2 flow, which means that the mean free path is shortened. Therefore, the energy of sputtered atoms during the deposition of TiN film could be reduced both by the decrease of the target power and the increase of N2 flow. In addition, the distance between target and substrate (Ts) in the condition (C) is increased to keep the uniformity of film property in the wafer. The condition (C) was poison mode as with the condition (A). The film properties of TiN (A), TiN (B) and TiN (C) film were investigated in detail below.

In the beginning, the residual stress in TiN (A), TiN (B) and TiN (C) film was evaluated. The residual stress in TiN film was calculated by Stoney’s equation with Si substrate Young’s modulus of 185 GPa and Poisson’s ratio of 0.28. The film thickness of TiN was measured for 17 points in the wafer with a diameter of 300 mm and the average area because of its low film density. Therefore, it is oxidized easily and contains large amount of O as shown in Figure 6. Based on the above results, the difference in the residual stress of TiN (A), TiN (B) and TiN (C) was considered with the difference in the composition and the grain structure. The large residual stress of TiN (A) arises from its coarse grain structure. In this test, the residual stress in Ti film with the thickness of 30 nm was also evaluated, and it was found to be about 100 MPa and less than that in TiN. Therefore, the residual stress of TiN (B) is lower than that of TiN (A) due to its composition. TiN (C) has a fiber-textured structure which many grain boundaries exist in the horizontal direction, resulting in less residual stress than TiN (A). Therefore, the residual stress in TiN film can be reduced by suppressing the grain growth due to the decrease in the energy of the sputtered atoms.

To investigate the etching performance for TiN and Ti-rich TiN film, the surface of TiN (A) and TiN (B) film after the etching process...
were observed using a SEM. The etching process was carried out in Cl₂-based plasma. The results are shown in Figure 9. The surface of TiN (A) showed the patterned indented surface due to the grain structure of TiN (A) and no residues were observed on the surface of TiN (A) film, which indicates that the etching performance of TiN (A) is good. Therefore, the etching performance for TiN (C) is also good because TiN (C) film has the same composition as TiN (A) one as shown in Figure 6. On the other hand, the surface of TiN (B) film showed a lot of residues due to the reaction of Ti and Cl₂ gas. This is because N disperses into Ti and does not form an intermetallic compound with Ti. It means that TiN(B) film deposited under metallic mode is unstable and TiN (B) mask has a serious effect on the device property. Therefore, TiN (B) film is not appropriate as a mask in the MHM process for Cu interconnects despite the residual compressive stress in TiN (B) is less than half that in TiN (A).

**Filling performance with fiber-textured TiN mask.**—Based on the result of the etching performance with the blanket wafer as shown in Figure 9, TiN (A) and TiN (C) film were applied as hard masks in the MHM process for Cu single damascene structure fabricated with 32 nm node technology. For the basic evaluation, the trench at a simple L/S pattern after the etching process with Cl₂-based plasma was observed using a SEM. The results are shown in Figure 10. The residue and the undulation of dielectric lines were not observed, and the line patterning looked good. Therefore, it is found that TiN (C) film has the same etching performance as TiN (A).

To investigate the effect of TiN (C) mask on the trench deformation after the etching process, the shape of the trench at a specific pattern with TiN (C) mask was observed using a cross sectional TEM and compared to that with TiN (A). The results are shown in Figure 11. The dielectric ridge at the opening of the trench with TiN (A) mask deformed as shown in Figure 2. On the other hand, no dielectric ridge with TiN (C) mask deformed at a specific pattern and the shape of trench was excellent. Figure 12 shows the normalized trench width at a specific pattern with TiN (A) and TiN (C) mask after the etching process. The trench width after the etching process using TiN (A) mask was below the target. On the other hand, the trench width with TiN (C)
Figure 13. Top view SEM images of the trench at a specific pattern with TiN (A) and TiN (C) mask after Cu electroplating and the CMP process.

Figure 14. Number of voids formed inside the trench at a specific pattern with TiN (A) and TiN (C) mask after Cu electroplating and the CMP process.

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