

# Study of plasma-induced damage of porous ultralow-*k* dielectric films during photoresist stripping

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Plasma damage of low-*k* dielectrics during photoresist (PR) stripping in a dual-damascene process is a critical issue in the application of copper/low-*k* technology for  $\leq 45$  nm nodes to increase the signal processing speed of integrated circuit devices. In this article, a detailed and systematic work has been conducted to study the low-*k* damage on porous methyl silsesquioxane ultralow-*k* films using various PR strip chemistries and process conditions on a high density plasma reactor. The experimental results obtained from different test methodologies show that the low-*k* damage generated under fixed process conditions increases in the order of  $\text{NH}_3 < \text{N}_2 < \text{H}_2/\text{N}_2 < \text{H}_2 < \text{O}_2$ . Among plasma control parameters, bias power has a very pronounced effect on low-*k* damage for reducing chemistries due to the acceleration of Si-C bond breaking by ion bombardment. Source power also affects the low-*k* damage significantly as it controls the ion density and flux to the wafer surface. The pressure effect is more complicated and shows different characteristics for oxidizing and reducing chemistries. The extent of low-*k* damage depends on the orientation of the wafer surface exposed to the plasma, leading to different sensitivity of the damage to the strip chemistry and process condition. Based on this work, an optimized chemistry and process regime are identified to effectively reduce low-*k* damage and achieve good strip process performance. © 2007 American Vacuum Society. [DOI: 10.1116/1.2431349]

## I. INTRODUCTION

As the device feature size of integrated circuit continues to scale, the bottleneck of the signal processing speed has shifted from the transistor portion to the global interconnect portion where the resistance-capacitance (*RC*) delay becomes a dominant factor.<sup>1</sup> To reduce the *RC* time constant, copper replaces higher resistance aluminum in wiring, and low-*k* material replaces silicon oxide as the interlayer dielectrics.<sup>2-4</sup> Many of the low-*k* dielectric materials being used or developed contain a high content of carbon. In order to further reduce the *k* value, the materials are also being made porous.<sup>5</sup> The increasing carbon content and porosity, however, degrade the mechanical strength of the low-*k* films and make them more vulnerable to physical and chemical damages during Integrated circuit (IC) chip fabrication. In the standard dual-damascene process flow to create copper interconnect and contacts, several different plasma etching and cleaning steps are performed directly on the low-*k* film. Among them the PR stripping steps using O<sub>2</sub> chemistry have been found to most severely damage the low-*k* film. Because the O<sub>2</sub> plasma readily removes the carbon in the film and forms a SiO<sub>2</sub>-like layer on the film surface, both dielectric constant and leakage current increase. All ultralow-*k* dielectrics ( $k < 2.4$ ) are porous and the film degradation rate will

be much higher basically due to the larger surface area that the porosity imposes. The large area exposed to plasma results in more low-*k* damage.<sup>6-9</sup> Therefore, preserving the *k* value of the ultralow-*k* materials during PR stripping has become a major challenge for next generation IC device processing.<sup>10</sup>

In this work, we have studied the performance of the PR strip process on a porous methyl silsesquioxane (MSQ) ultralow-*k* film. MSQ film consists of a significant amount of methyl (CH<sub>3</sub>) groups to reduce the film polarization and get a low dielectric constant. Porous MSQ film contains a high density of nanometer-size pores so the dielectric constant is further reduced. This type of film has a very low-*k* value ( $k < 2.4$  for porosity  $> 20\%$ ) and its film properties are sensitive to plasma process conditions. Therefore, porous MSQ is a good candidate for the investigation of low-*k* damage during PR stripping. Various chemistries, including O<sub>2</sub>, H<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>/N<sub>2</sub>, and NH<sub>3</sub>, and process conditions have been used in this work to study the low-*k* damage in a high density plasma reactor. By using different analytical methodologies and electrical tests for the ultralow-*k* film, the effects of chemistry and process parameters have been characterized. To understand the role of wafer surface geometry on low-*k* damage, both blanket and patterned MSQ films were used for the tests. Based on the results obtained from this study, an optimized chemistry and process regime have been identified to achieve good process performance in PR stripping while minimizing the plasma damage to the low-*k* film.

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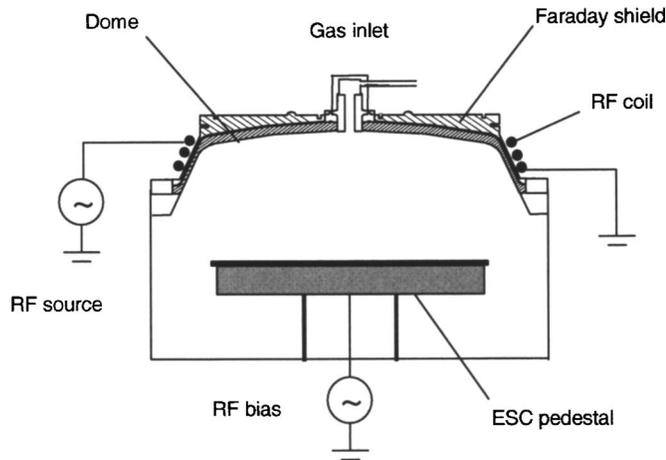


FIG. 1. Schematic diagram of eHighlands plasma reactor.

## II. EXPERIMENT

This work was performed in an Aspen III eHighlands system from Mattson Technology. Each process chamber has two separate plasma zones, thus two wafers can be processed at the same time. Each plasma zone has its own radio frequency (rf) system for plasma generation and control, but they share the same gas line and pump. As illustrated in Fig. 1, the high density plasma is generated by a rf power (source power) of 13.56 MHz applied to an inductive coil on a dielectric dome, which is set on a Faraday shield mounted on the top plate of the chamber. The Faraday shield is grounded to filter out the capacitive coupling. An electrostatic chuck holds the wafer on a cathode pedestal. A separate rf power (bias power) of 13.56 MHz is applied to the cathode to control ion bombardment energy to the wafer surface. The pedestal temperature is set to 10 °C during the process by a chiller and the wafer temperature is controlled by backside helium cooling. The chamber is evacuated by a turbomolecular pump and an inline dry mechanical pump. Process gases are introduced through the nozzle at the top of the dome with controlled flow rates. Chamber pressure is maintained at a designated value with a throttle valve. Process endpoint control is done by an optical emission spectroscopic system.

The blanket low- $k$  wafers have 1000 Å thick porous MSQ films spin coated on silicon substrates. They are used to study the low- $k$  damage on the surface directly exposed to plasma. The low- $k$  damage on these wafers after plasma exposure is evaluated by the shift in dielectric constant obtained from capacitance-voltage ( $C$ - $V$ ) measurements using a mercury probe operating at 1 MHz. The film thickness of each sample is measured to calculate the dielectric constant from the capacitance data. Since the low- $k$  damage only occurs in the top portion of the film, the  $k$  value thus obtained is an effective value across the whole film. The patterned low- $k$  wafers have a line-space structure formed through plasma etching on 2500 Å thick porous MSQ. On the top of the low- $k$  film is a 500 Å thick oxide hard mask and around 3000 Å thick deep ultraviolet PR. These wafers are mainly

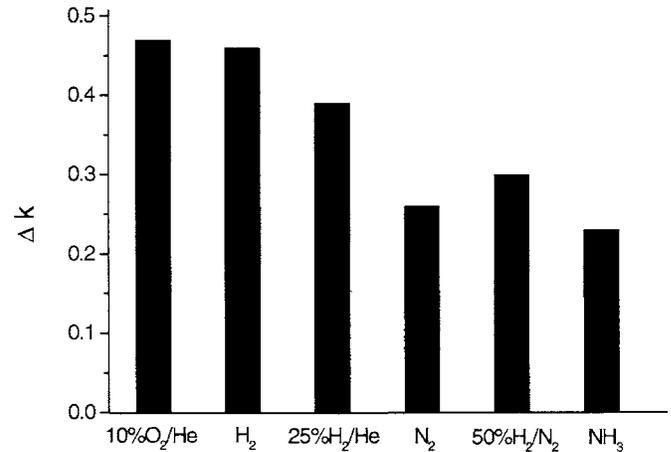


FIG. 2. Effect of strip chemistry on  $k$ -value change. Source power=600 W, bias power=75 W, pressure=10 mTorr, plasma exposure time=15 s.

used to study the low- $k$  damage to the pattern sidewall during the PR stripping. The damage is evaluated by profile distortion inspected by a scanning electron microscope (SEM). The samples are also dipped in 1% HF solution for 30 s to remove the damaged layer on the sidewall to check the extent of the low- $k$  damage. Line capacitance and  $RC$  constant, as well as breakdown field intensity, are measured after several sequential process steps are completed, including the deposition of a copper liner and copper, chemical-mechanical polishing of the copper and cap layer, and deposition of a passivation layer. The atomic composition profile perpendicular to the sidewall is also analyzed by electron energy loss spectroscopy (EELS). Due to the limitation of wafer supplies at the time of this work, the blanket porous MSQ wafers used were 200 mm, while the patterned wafers were 300 mm. Although the two sets of studies on blanket and patterned wafers and their results are relatively independent, bias power scaling was made during the tests according to different sizes of the cathode pedestals in case some correlation was needed later. In addition to low- $k$  wafers, blanket PR wafers were used to measure PR strip rate.

## III. RESULTS AND DISCUSSION

### A. Low- $k$ damage on blanket wafers

Low- $k$  damage of a certain low- $k$  dielectric film during plasma processing is determined by the type of chemistry used and the process condition. In this section, the effects of these factors are demonstrated on blanket porous MSQ wafers. Since blanket wafers are subjected to vertical ion bombardment in the plasma and the intensity of ion bombardment is controlled by various process parameters, the study of the low- $k$  damage on blanket wafers provides direct information on the characteristics and mechanism of the damage.

#### 1. Effect of strip chemistry

The results of low- $k$  damage under fixed process conditions and time with different chemistries used for PR stripping are given in Fig. 2. As expected, O<sub>2</sub> plasma causes the

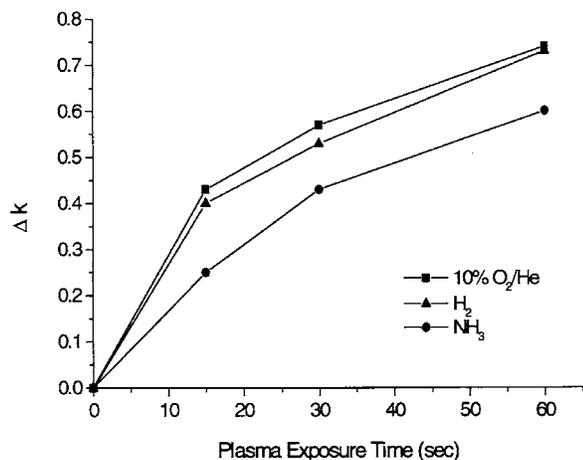


FIG. 3. Dependence of  $k$ -value change on plasma exposure time. Source power=600 W, bias power=75 W, pressure=10 mTorr.

most severe low- $k$  damage by generating a significant increase in  $k$  value even when it is highly diluted with He. However, the  $k$ -value change ( $\Delta k$ ) for the H<sub>2</sub> plasma is surprisingly large as it is very close to that of O<sub>2</sub> plasma. Dilution of the H<sub>2</sub> plasma with He helps to reduce the damage but the effect is very limited. The  $\Delta k$  in N<sub>2</sub> plasma is much lower than that in O<sub>2</sub> and H<sub>2</sub> cases. Adding H<sub>2</sub> into N<sub>2</sub> brings the  $\Delta k$  up again as shown for the equally mixed H<sub>2</sub> and N<sub>2</sub>. However, when NH<sub>3</sub> is used, the best performance is obtained. Based on these results, it is expected that hydrogen-free radicals can break Si-C bonds or abstract H atoms from C-H<sub>x</sub> matrix easily under ion bombardment. Moreover, hydrogen-free radicals can also diffuse deeper into the low- $k$  film than oxygen-free radicals because of their small size and cause damage in the region below the surface.<sup>11</sup> On the other hand, the contribution of hydrogen to the low- $k$  damage depends significantly on the hydrogen source, such as H<sub>2</sub>/N<sub>2</sub> mixture or NH<sub>3</sub>.

The extent of low- $k$  damage increases with plasma exposure time. As shown in Fig. 3, the  $k$  value changes rapidly during the initial 10 s of exposure, especially in the diluted O<sub>2</sub> and H<sub>2</sub> plasmas, and increases more slowly afterwards. Since the plasma exposure time needed for PR stripping depends on the PR strip rate for a certain thickness of PR, the results of Fig. 3 actually indicates that the reducing chemistry can cause more damage than the oxidizing chemistry to the surface not covered by PR and exposed to direct ion bombardment because its PR strip rate is lower and thus a longer strip time is needed.

To evaluate the chemical efficiency of PR stripping against the low- $k$  damage, the PR strip rates for the chemistries discussed were measured on blanket PR wafers using the same conditions as in the low- $k$  damage tests, and the ratios of  $\Delta k$  to strip rate were calculated. As shown in Fig. 4, the O<sub>2</sub> plasma gives the highest PR strip rate as expected. Among other chemistries, H<sub>2</sub> and N<sub>2</sub> plasma strips PR very slowly, H<sub>2</sub>/N<sub>2</sub> mixture accelerates PR stripping, while NH<sub>3</sub> shows an even higher strip rate. Figure 5 gives the ratio data normalized to the value for O<sub>2</sub>. A higher ratio corresponds to

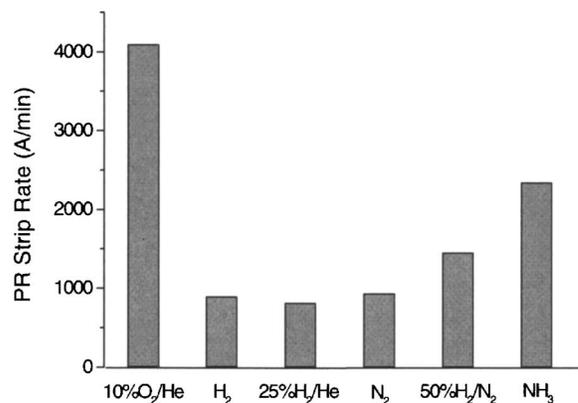


FIG. 4. PR strip rates with different chemistries. Source power=600 W, bias power=75 W, pressure=10 mTorr.

lower strip efficiency since more severe low- $k$  damage will be generated after a fixed thickness of PR is stripped. The results clearly indicate that due to their slow PR strip rates, both H<sub>2</sub> and N<sub>2</sub> chemistries have much lower strip efficiency than that of O<sub>2</sub> chemistry against the low- $k$  damage. H<sub>2</sub>/N<sub>2</sub> mixture gives higher strip efficiency. But NH<sub>3</sub> chemistry again produces the best result among all chemistries.

Based on the unique performance of NH<sub>3</sub>, it is interesting to study the mixture of H<sub>2</sub> and N<sub>2</sub> further for PR stripping over ultralow- $k$  dielectrics. Figure 6 gives the  $\Delta k$  value for the porous MSQ film in H<sub>2</sub>/N<sub>2</sub> plasma as a function of the N<sub>2</sub> percentage in the total flow of H<sub>2</sub> and N<sub>2</sub>. The linear change of the  $k$  value with N<sub>2</sub> concentration indicates that the major effect of N<sub>2</sub> on the extent of low- $k$  damage is through dilution. The low- $k$  damage to porous MSQ film in pure N<sub>2</sub> plasma has been found to be the lowest among all chemistries investigated for a fixed plasma exposure time. This can be explained by a less favorable reaction of nitrogen with the Si-CH<sub>3</sub> group.<sup>12</sup> On the other hand, Fig. 7 shows the PR strip rate as a function of N<sub>2</sub> percentage. The dependence of PR strip rate on N<sub>2</sub> percentage is highly nonlinear. Pure H<sub>2</sub> and N<sub>2</sub> plasmas remove PR very slowly. The strip rate increases as N<sub>2</sub> concentration increases and peaks at

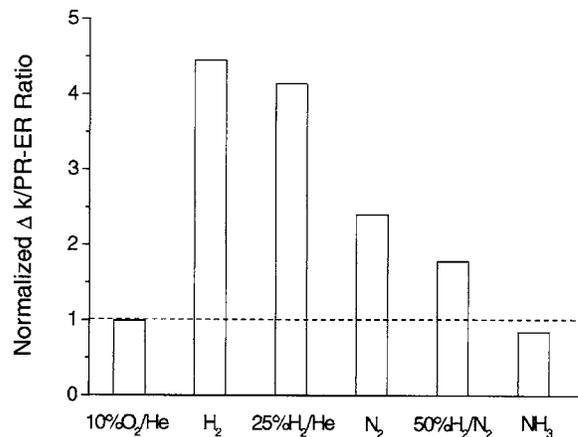


FIG. 5. Normalized  $\Delta k$ /PR-ER ratio with different chemistries. Source power=600 W, bias power=75 W, pressure=10 mTorr.

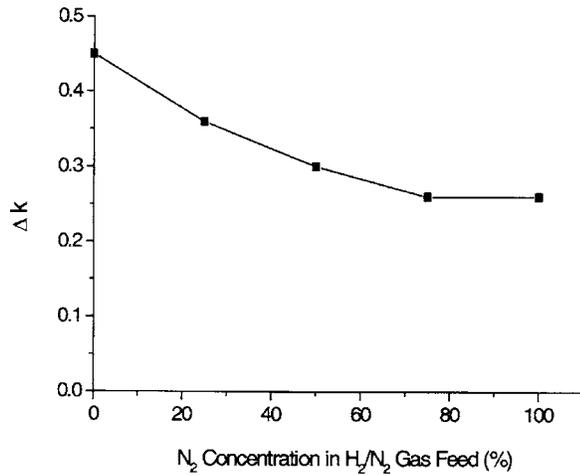


FIG. 6. *k*-value change as a function of N<sub>2</sub> concentration in H<sub>2</sub>/N<sub>2</sub> gas feed. Source power=600 W, bias power=75 W, pressure=10 mTorr, plasma exposure time=15 s.

around 20% of N<sub>2</sub> addition, and then decreases gradually to that at 100% H<sub>2</sub>. This result means that the role of N<sub>2</sub> in PR stripping is different from that in low-*k* damage. It is expected that the species of NH<sub>x</sub> formed in the H<sub>2</sub>/N<sub>2</sub> plasma can accelerate the PR stripping. Over the entire N<sub>2</sub> concentration range, the Δ*k* value of the H<sub>2</sub>/N<sub>2</sub> plasma is larger and the PR strip rate is lower than those of the NH<sub>3</sub> plasma. The NH<sub>3</sub> plasma thus appears to have its own uniqueness that cannot be simulated by mixing H<sub>2</sub> and N<sub>2</sub> together.

## 2. Effect of process conditions

Figure 8 shows the Δ*k* value of the porous MSQ films after they are exposed to O<sub>2</sub>, H<sub>2</sub>, and NH<sub>3</sub> plasmas at different bias powers while other process conditions and time remain unchanged. In all cases, the low-*k* damage increases with bias power as ion bombardment accelerates carbon bond breaking in the film. But the extent of the damage and characteristics are not the same for different chemistries. Low-*k* damage is severe even at the low bias power and

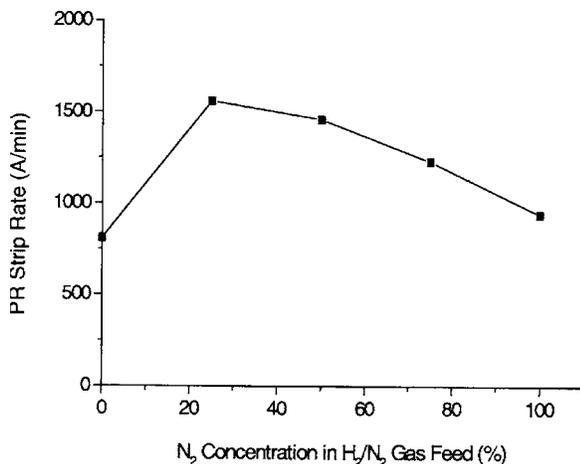


FIG. 7. PR strip rate as a function of N<sub>2</sub> concentration in H<sub>2</sub>/N<sub>2</sub> gas feed. Source power=600 W, bias power=75 W, pressure=10 mTorr.

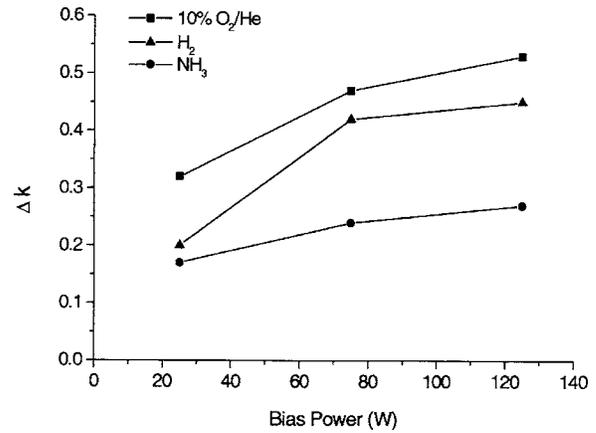
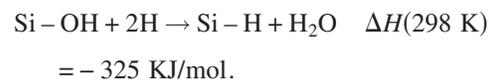
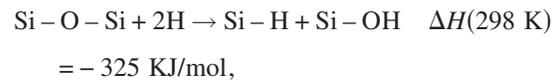
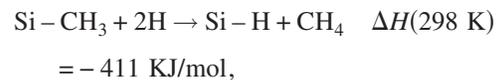


FIG. 8. Dependence of *k*-value change on bias power. Source power =600 W, pressure=10 mTorr, plasma exposure time=15 s.

becomes worse as bias power increases in O<sub>2</sub> plasma. This is because the carbon content in the low-*k* film is readily reduced by oxygen and Si–O bonds are formed quickly. The *k*-value change is the smallest for NH<sub>3</sub> chemistry, and it increases more slowly with increasing bias power. The most significant bias power effect is seen in H<sub>2</sub> plasma. At the low bias power, the low-*k* damage is very close to that in NH<sub>3</sub> plasma but approaches rapidly to the damage level of O<sub>2</sub> plasma as bias power is increased, indicating that the ion bombardment is the major driving force to generate low-*k* damage for H<sub>2</sub> chemistry.

The characteristics of low-*k* damage in H<sub>2</sub> plasma can be better understood by looking at the chemical reactions involved. As proposed by Worsley *et al.*,<sup>11</sup> the damage to porous organosilicate glass dielectrics, including MSQ, in H<sub>2</sub> plasma occurs through the following reactions:



Compared to O<sub>2</sub> chemistry, hydrogen species can break any of the four silicon bonds and form different by-products, so in principle they can cause more serious damage. However, these reactions are more difficult than those caused by O<sub>2</sub> thermodynamically since the Δ*H* values for the above reactions are much smaller than that for an oxidation reaction (Δ*H* ~ -1000 KJ/mol). As a result, the low-*k* damage in H<sub>2</sub> plasma will be less severe without strong ion bombardment. But under ion bombardment more severe damage can be generated, especially when a longer process time is needed to strip a certain thickness of PR.

The effect of source power on low-*k* damage is given in Fig. 9. Since the source power basically controls only the

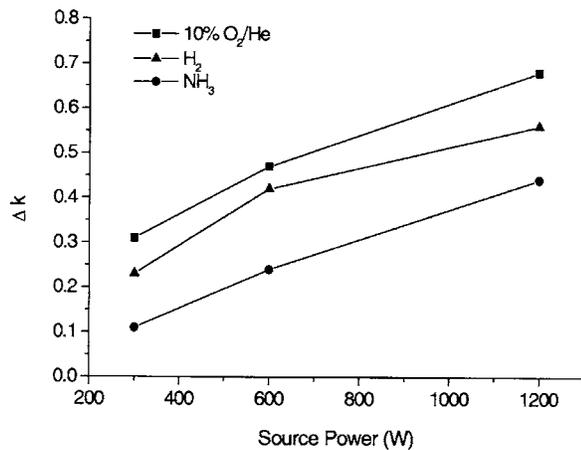


FIG. 9. Dependence of *k*-value change on source power. Bias power = 75 W, pressure = 10 mTorr, plasma exposure time = 15 s.

plasma density and does not affect the ion bombardment energy, the dependence of the damage on source power is determined by how the ion density changes with source power. The latter is almost linear in the current process regime so the  $\Delta k$  increases quite linearly with increasing source power.

In addition to bias power and source power, pressure is another key process parameter to affect the low-*k* damage, and its effect is a little more complicated as shown in Fig. 10. At lower bias power (75 W),  $\Delta k$  increases as pressure is raised in O<sub>2</sub> plasma but decreases in H<sub>2</sub> and NH<sub>3</sub> plasmas. Based on the previous discussion, this result can be explained as follows. In O<sub>2</sub> plasma, low-*k* damage is more free radical driven and does not need much ion bombardment. Since oxygen radical density increases but ion density decreases with increasing pressure, the low-*k* damage becomes worse. However, in the cases of H<sub>2</sub> and NH<sub>3</sub>, ion bombardment is needed to induce the damage. Because the ion density drops as pressure is raised, the extent of the low-*k* damage is reduced at higher pressure. At higher bias power

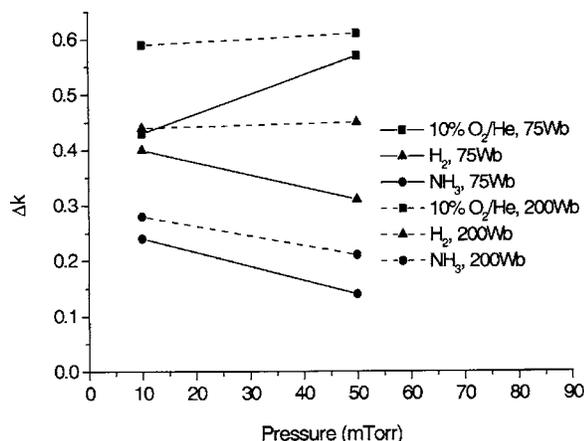


FIG. 10. Dependence of *k*-value change on pressure at different bias powers. Source power = 600 W, plasma exposure time = 15 s.

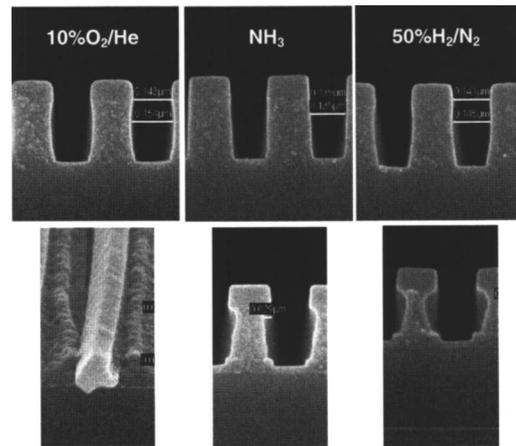


FIG. 11. Profile distortion of patterned MSQ film after PR stripping in different plasmas. Source power = 600 W, bias power = 300 W, pressure = 10 mTorr, 50% overetch. Upper row: before HF dip. Lower row: after HF dip.

(200 W), the pressure effect becomes less obvious, indicating that the roles of free radical density and ion density become less important.

## B. Low-*k* damage on patterned wafers

The low-*k* damage on the dual-damascene structures occurs on the bottom surface of the trench and the sidewalls of the trench and via. The extent of the damage on the trench bottom surface is similar to what discussed previously for the blanket films. But the pattern sidewall is not subjected to vertical ion bombardment; its damage is mainly caused by the impinging of scattered ions and shows some very different characteristics. Since the sidewall area is quite large, the low-*k* damage to it can still have a significant impact on capacitance and *RC* time constant. Reducing sidewall damage is thus a major consideration in developing PR strip processes for low-*k* films. To study the low-*k* damage on the sidewall during PR stripping, single-damascene patterned wafers with a line/space structure of porous MSQ with an oxide mask are used in this work.

### 1. Effect of strip chemistry

The extent of sidewall damage can be observed through profile distortion after PR stripping by dipping the stripped samples into a diluted 1% HF solution. Because the damaged layer on the MSQ film has a lower carbon content and dangling silanol bonds, it will dissolve in the HF solution and generate a profile undercut. Figure 11 shows the SEM cross section of the damaged profile after PR stripping in O<sub>2</sub>, H<sub>2</sub>/N<sub>2</sub>, and NH<sub>3</sub> plasmas. Before the HF dip, a bowing profile can be observed with O<sub>2</sub> plasma stripping. A similar profile can also be seen for H<sub>2</sub>/N<sub>2</sub> chemistry, but the bowing is less severe. No obvious profile distortion is observed for NH<sub>3</sub> chemistry. After the HF dip, an undercut profile shows up in all three cases. The profile undercut is so severe when O<sub>2</sub> is used that the line feature collapses, while the undercut generated by NH<sub>3</sub> chemistry is the least.

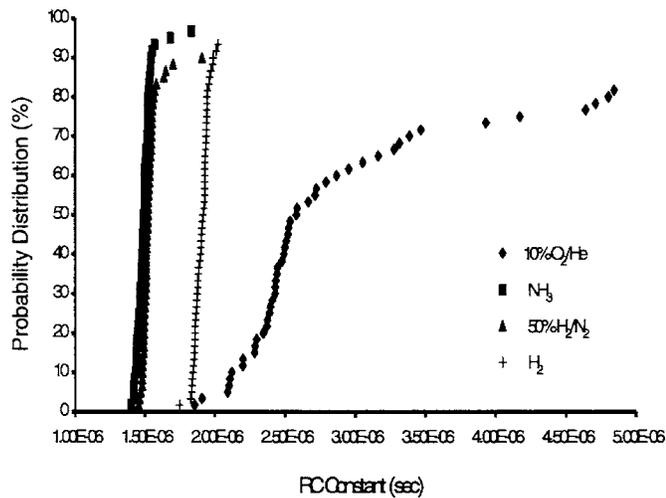


FIG. 12. Effect of strip chemistry of RC constant. Source power=600 W, bias power=300 W, pressure=10 mTorr, 50% overetch.

The effect of low- $k$  damage on electric performance was evaluated by the RC constant measurement done on single-damascene structure wafers. Figure 12 shows the results for different chemistries used for PR stripping. The RC constant is the largest for diluted O<sub>2</sub> plasma and improved for H<sub>2</sub>, H<sub>2</sub>/N<sub>2</sub>, NH<sub>3</sub>, and NH<sub>3</sub>/N<sub>2</sub> plasma in that order. Obviously, this trend shows a good correspondence between the RC constant and the  $\Delta k$  value on blanket wafers given in Fig. 2. However, a significant difference can be noticed on the extent of the damage for these two cases. While the  $\Delta k$  value generated in H<sub>2</sub> plasma is very close to that in O<sub>2</sub> plasma on blanket wafers, the RC constants obtained from H<sub>2</sub> plasma are much smaller than those from O<sub>2</sub> plasma on patterned wafers. This implies that the H<sub>2</sub> plasma causes less damage to the sidewall than to the top surface because of strong ion bombardment dependence. Another evaluation of the low- $k$  damage is the breakdown field intensity of the dielectric film. As shown in Fig. 13, the breakdown field intensity after PR stripping in diluted O<sub>2</sub> plasma is the lowest, while in NH<sub>3</sub> and NH<sub>3</sub>/N<sub>2</sub> plasmas it is the highest.

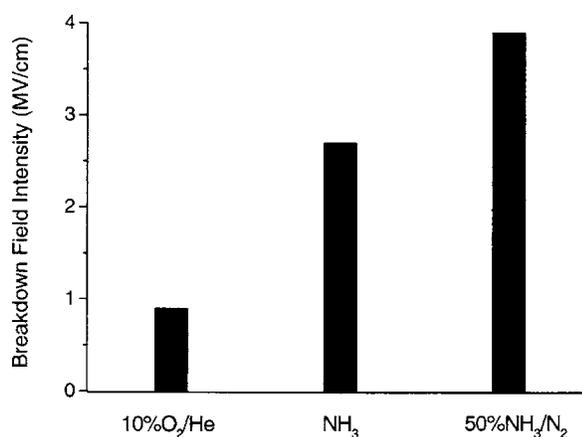


FIG. 13. Effect of strip chemistry on breakdown field intensity. Source power=600 W, bias power=300 W, pressure=10 mTorr, 50% overetch.

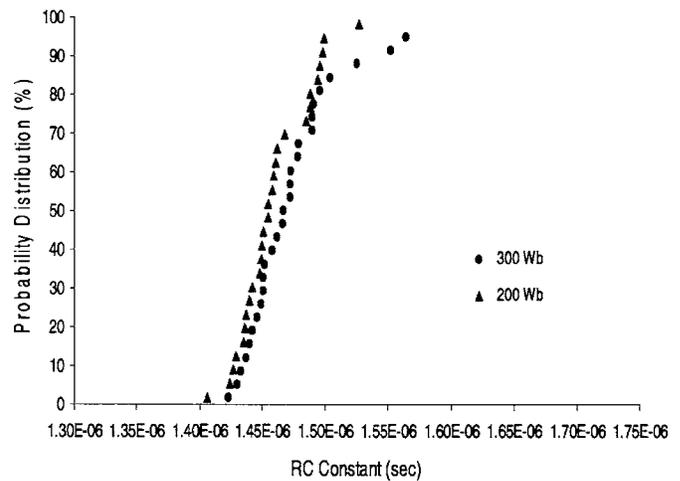


FIG. 14. Dependence of RC constant on bias power. Source power =600 W, pressure=10 mTorr, 50% overetch.

## 2. Effect of process conditions

Low- $k$  damage to the sidewall can be controlled by process conditions during PR stripping. The key is to reduce the energy and flux of the ions impinging on the sidewall. Figure 14 shows the effect of bias power on the RC constant for NH<sub>3</sub> chemistry. Although a higher bias tends to cause more damage on the sidewall, the actual effect is not significant in comparison with the case of blanket wafers. The reason for this result is quite simple as there is no direct and strong ion bombardment to the sidewall. Especially at low pressure, the ion bombardment anisotropy is quite high.

Compared to the bias power, it seems that the source power has a more significant effect on the sidewall damage. It is a general phenomenon in plasma etching that higher source power usually causes more isotropic etching to the sidewall and generates an undercut or bowing profile due to more ion impinging. This also seems to be true in the case of low- $k$  damage. As shown in the SEM pictures in Fig. 15 for the patterned MSQ wafers after PR stripping and HF dip, higher source power does produce more profile undercut. The source power effect on the low- $k$  damage also shows up clearly on the RC constant measurement. Higher source power causes more RC delay as given by Fig. 16.

Figure 17 shows the pressure effect on RC constant. Similar to the results on blanket films, higher pressure helps to reduce low- $k$  damage to the sidewall for NH<sub>3</sub> chemistry. Because the plasma density is lower at higher pressure and the low- $k$  damage generated by the reducing type of chemistries is ion driven as discussed previously, the extent of damage for these chemistries is thus lower.

Based on the process and electric performances discussed in this article, NH<sub>3</sub> chemistry is a good selection for PR stripping over low- $k$  film. In order to better understand the property change in the low- $k$  film after PR stripping in NH<sub>3</sub> plasma, EELS is used to study the film composition in the direction perpendicular to the sidewall after copper liner (tantalum) and copper deposition. The result given in Fig. 18 shows a transition layer about 50 Å thick at the interface

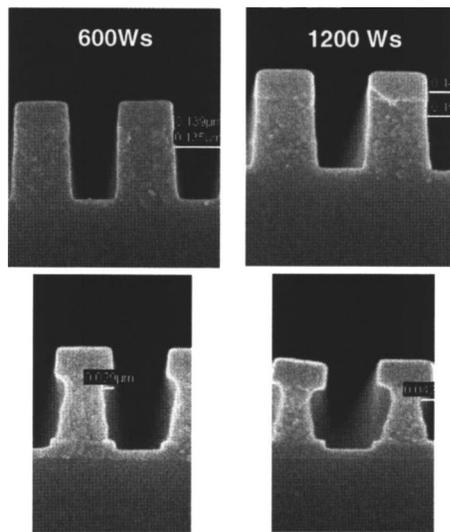


FIG. 15. Profile distortion of patterned MSQ film after PR stripping at different source powers. Bias power=300 W, pressure=10 mTorr, 50% overetch. Upper row: before HF dip. Lower row: after HF dip.

between the copper liner and the low-*k* film. The carbon depletion is not obvious in this layer. Instead a carbon-rich region can be seen, which probably is due to the remaining polymer deposition generated in the previous trench etch step that was not removed by the PR stripping with the percentage of over strip conditions used in these experiments. The nitrogen content inside the low-*k* film is very low, eliminating the concern about possible PR poisoning in the trench lithography step in the dual-damascene process flow.

#### IV. CONCLUSION

The low-*k* damage of porous MSQ film during PR stripping depends significantly on the strip chemistry and process conditions. On blanket wafers where the film surfaces are directly exposed to the plasma, O<sub>2</sub> chemistry generates very

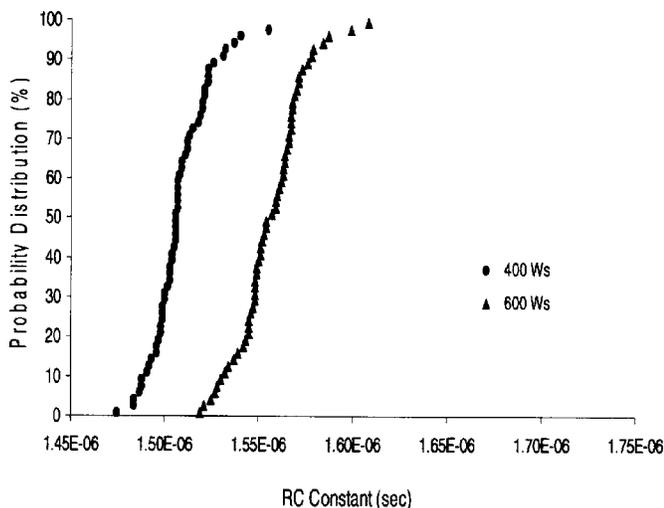


FIG. 16. Dependence of RC constant on source power. Bias power=300 W, pressure=10 mTorr, 50% overetch.

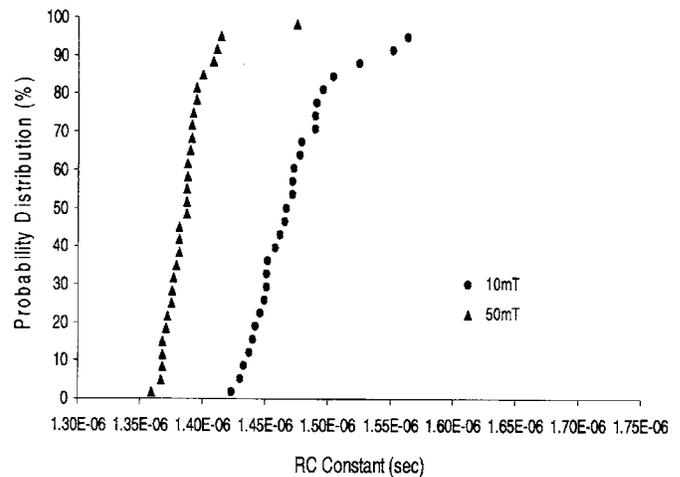


FIG. 17. Dependence of RC constant on pressure. Source power=600 W, bias power=300 W, 50% overetch.

severe damage with a large change in *k* value. Among several other chemistries studied, H<sub>2</sub> plasma also causes almost the same amount of damage as O<sub>2</sub> plasma within a fixed process time, N<sub>2</sub> and NH<sub>3</sub> generate the least damage, and the H<sub>2</sub>/N<sub>2</sub> mixture produces a result somewhere in between. By taking the PR strip rate into consideration, the chemical efficiency of PR strip against the low-*k* damage shows the order of NH<sub>3</sub> > H<sub>2</sub>/N<sub>2</sub> > O<sub>2</sub> > N<sub>2</sub> > H<sub>2</sub>. The lowest strip efficiency of H<sub>2</sub> chemistry is due to the high reactivity of hydrogen radicals with Si-CH<sub>3</sub> bonds in the low-*k* film under ion bombardment and low PR strip rate. On the other hand, the highest strip efficiency of NH<sub>3</sub> is attributed to the low low-*k* damage and high PR strip rate, making this chemistry a good candidate for PR stripping over ultralow-*k* dielectric materials. In addition to chemistry, bias power has a very pronounced effect on low-*k* damage due to the sensitivity of Si-CH<sub>3</sub> breaking processes to ion bombardment energy, especially for reducing chemistries. Higher bias power always leads to greater change in *k* value. Low-*k* damage also increases with increasing source power due to higher ion density and flux to the surface. The pressure effect is different for different chemistries. For O<sub>2</sub>, higher pressure generates more damage because the damage is free radical driven and the free radical density increases when pressure is raised. However, the damage becomes less for NH<sub>3</sub> chemistry at higher pressure because the damage is ion driven in this case and ion density drops significantly with increasing pressure.

On patterned wafers, low-*k* damage on the sidewall has a major contribution to the electrical performance. As in the case of blanket wafers, O<sub>2</sub> plasma causes the most severe damage to the sidewall, resulting in a large RC constant and low breakdown field intensity. On the other hand, NH<sub>3</sub> plasma has some of the best values for these parameters. The result for H<sub>2</sub> chemistry is between the two extreme cases. Compared to blanket wafers, the RC constant obtained from H<sub>2</sub> plasma is much smaller than that from O<sub>2</sub> after the same thickness of PR is stripped. Therefore, the chemical efficiency of the PR strip compared with the low-*k* damage on

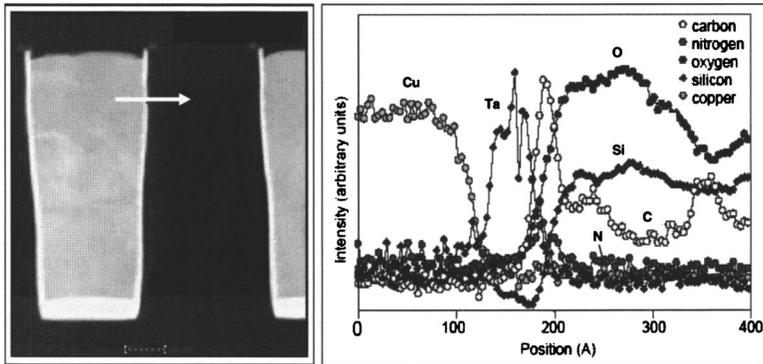


FIG. 18. Atomic composition of the porous MSQ film in the direction perpendicular to the sidewall after PR stripping.

the sidewall shows a different order of  $\text{NH}_3 > \text{H}_2/\text{N}_2 > \text{H}_2 > \text{O}_2$ . Obviously, this trend is caused by the difference in ion bombardment intensities between the sidewall and the top surface. Electrical performance also depends on process conditions. Higher bias power and source power tend to generate more severe low-*k* damage in general. Higher pressure increases the damage for  $\text{O}_2$ -based chemistry but does the opposite for reducing chemistries. Based on all of the results obtained from this work,  $\text{NH}_3$  seems to be a good chemistry for PR stripping over ultralow-*k* material. By using this chemistry together with appropriate process conditions, an optimized process performance can be achieved.

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