Copper has replaced Al in integrated circuit interconnects to reduce the RC delay and to achieve higher electromigration reliability, where R and C represent distributed resistance and capacitance contained in circuits, respectively. The RC delay corresponds to how quickly a voltage or current can be switched on and off. Copper interconnects are fabricated by cost-effective dual-damascene technology which is different from conventional Al subtractive technology. In the dual-damascene process, a columnar hole is etched using trench-first or via-first method into the interlayer dielectric (ILD) before filling the structure up with copper. Chemical mechanical polishing (CMP) is done to polish back the metal to ILD surface. The electromigration mechanism in such interconnects is different from that in Al interconnects and it may not be significantly better than Al interconnects as anticipated. Interface diffusion dominates electromigration in Cu interconnects as opposed to grain boundary diffusion in Al interconnects. This is further amplified in submicrometer interconnects as the bamboo grain structure eliminates the grain boundary diffusion. With scaling of Cu interconnect dimensions in submicrometer range, the surface-to-volume ratio increases and is found to cause corresponding increase in electromigration. Although various electromigration damage paths exist in Cu interconnects, Cu/dielectric cap interface is reported to be the fast electromigration path in most of the studies.

To improve electromigration performance of dual-damascene Cu interconnects, the fast electromigration path (i.e., the Cu/dielectric interface) must be improved. Although this improvement was demonstrated by altering the Cu/dielectric interface using selective electroless metal coating on top Cu surface, the effect of Cu/dielectric cap interface modifications on electromigration behavior of upper and lower layer dual-damascene structures was not attempted by these workers. The effect of Cu/dielectric interface modification in upper and lower dual-damascene structures may not be the same due to proposed different electromigration mechanisms in these dual-damascene structures. Also, a significant asymmetry in electromigration behavior of upper and lower layer structures was observed in our studies. In order to investigate this, Cu/dielectric cap interface was modified using different Cu surface treatments after CMP and its effect on electromigration in upper and lower layer dual-damascene structures was studied.
carried out to investigate interface chemistry and depth profile before electromigration (EM) tests in a Kratos AXIS spectrometer (U.K.) with the monochromatic Al Kα X-ray radiation at 1486.71 eV. The base vacuum in XPS analysis chamber was about 10^{-9} Torr.

**Results**

**XPS analysis.**— In order to understand the Cu/SiNx interfacial reaction in terms of different treatments, XPS depth profile and detailed core level spectra analysis were conducted. Figure 2 gives the XPS depth profile of Cu/SiNx interfaces for the control specimen. It is noted that the depth profiles with treatments are not apparently different. The Cu/SiNx interface is well defined because there is no tail of any element observed in the depth profiles in Fig. 2. It is seen that the atomic ratio N/Si in the present SiNx film is around 1.1.

There is an oxygen peak O1s with ~10% atomic concentration located at the Cu/SiNx interface. This oxygen content is probably due to oxygen or moisture absorption during CMP process.

Figure 3 shows the details of the Si 2p, N 1s, and Cu 2p_{3/2} spectra with respect to different sputtering time (depth) for the pristine specimen. The sputtering times (ST1 to ST4) are indicated as the dashed vertical lines in Fig. 2. As expected, with the progress of sputtering, Si 2p and N 1s become weaker and weaker, while Cu 2p_{3/2} spectra turn out to be stronger and stronger.

To further examine the effect of different treatments on the interface bond formation, Fig. 4-6 compare the spectra deconvolution of N 1s, Si 2p, and Cu 2p_{3/2} for all four cases at ST2, respectively. Figure 4 shows that the N 1s core level spectra of the Cu/SiNx interface can be deconvoluted into two peak components at the binding energies of 397.9 and 399.4 eV, associated with the N–Si bond (Ref. 11) and the N–Cu complex, respectively. Similar amount of nitrogen atoms are bonded to Cu for the SiH4-treated specimen. The Cu–N bonds are much less for pristine and H2-treated specimens. A detailed discussion is given later.

Figure 5 shows that, for the cases with H2 and SiH4 treatment, the Si 2p core level spectra can be deconvoluted into two peaks at the binding energies at 100.2 and 101.8 eV, assigned to Si–Cu and Si–N bonds, respectively. However, for the cases without treatment and with NH3 treatment, the peak corresponding to the Si–Cu bond disappear, indicating that no Si–Cu bonds form at the interface, or its content is under the detectable limit.

Figure 6 clearly indicates that the Cu 2p_{3/2} peak is centered at 932.5 eV, which could be assigned to Cu0 or Cu2O (Ref. 14) for the control specimen and the one with NH3 treatment. However, when the specimens are subject to H2 or SiH4 treatments, the Cu 2p_{3/2} peak shifts to 932.9 eV, corresponding to the Cu–Si bond. This observation agrees well with Fig. 5.

Figure 7 shows the relative amount of N and Si atoms bonded to Cu in terms of different treatment processes. All the data are extracted from the deconvolution analysis from Fig. 4 and 5. It is seen that less than 5% N atoms and no Si atoms are bonded to Cu if no treatment is imposed. This is mainly attributed to the passivated Cu...
surface after CMP. A high N/(Cu/N_total) ratio (≈30%) for the
NH3-treatment case was observed, which indicates that a large num-
er of nitrogen atoms have been successfully bonded to the Cu
surface. Once the NH3 plasma treatment is applied, the copper sur-
face will be activated, which in turn reacts with the nitrogen and
forms a copper nitride layer. It is known that copper nitride is an
anti-ReO3 structure with Cu atoms occupying the center of the cubic
edges and N atoms occupying the corners of the cell. Its lattice
parameter is around 0.38 nm, which is slightly larger than that of Cu
(≈0.36 nm). The lattice mismatch could be negligible. Thus, a
dense copper nitride film will form, which will prevent the Cu–Si
bond formation during the subsequent SiNx deposition. As a result,
there is no Cu–Si bond observed in NH3 treated specimen (Fig. 5b
and 6b). If the Cu surface is treated with H2 plasma, it will also be
activated. Both Cu–N and Cu–Si bonds will form simultaneously.
This is the reason that around 15% N and 30% Si atoms are bonded
to Cu for H2 treated specimen. Upon the SiH4 plasma treatment, the
Cu surface will be covered by the CuSi thin layer. However, due to
the high kinetic energy of Si and H ions, which may resputter the
bonded Si atoms, some Cu–Si bonds will be broken. Therefore, the
copper surface will be exposed partially. During the subsequent SiNx
deposition, active N atoms thus have chances to bond to Cu to form
some Cu–N bonds, as observed in Fig. 7.

Electromigration testing results.— The lognormal plot of failure
times of upper layer (M-2) and lower layer (M-1) structures with
different surface treatments are shown in Fig. 8a and b, respectively.
The mean-time-to-failure (MTF) data for both M-1 and M-2 struc-
tures with different surface treatments are listed in Table I. It is
clearly observed that the electromigration failure times are improved
due to surface treatments. NH3 treated samples showed similar fail-
ure times as control samples with no surface treatment. Significant
improvement was observed for hydrogen plasma and silane treat-
ment structures. Contrary to concerns over electromigration behav-
ior of lower layer structures,1 it was observed that the surface treat-
ments improved electromigration performance of lower-layer struc-
tures similar to upper-layer structures. Hydrogen plasma and
silane treatment showed significantly reduced early failures.

Typical FIB cross-section images of upper- and lower-layer
structures after failure are shown in Fig. 9a and b, respectively. In
both these cases, the electromigration-induced void location bor-
dered the Cu/dielectric cap interface and voids were not observed
near the Cu/Ta interfaces.

Figure 3. The details of the (a) Si 2p, (b) N 1s, and (c) Cu 2p3/2 spectra with respect to different sputtering time (depth) for the pristine specimen.

Figure 4. Deconvolution of N 1s spectra (a) without treatment, (b) with
NH3, (c) with H2, and (d) SiH4 treatments.

Figure 5. Deconvolution of Si 2p spectra (a) without treatment, (b) with
NH3, (c) with H2, and (d) SiH4 treatments.
Discussion

Electromigration performance has been found to be directly correlated to adhesion between Cu and the dielectric cap layer. It is suggested that the surface treatments modify the Cu/dielectric cap interface leading to change in adhesion between Cu and dielectric cap, which in turn influences the Cu/dielectric cap interface dominated electromigration. NH\textsubscript{3} treatment is reported to cause the reduction of copper oxide as well as formation of CuN leading to a better Cu/SiN interface. This is also supported by the present XPS analysis (Fig. 4). Hydrogen plasma treatment is known to form hydride on the Cu surface with no change in microstructure and to clean the Cu surface 19 providing better adhesion between Cu and subsequently deposited silicon nitride dielectric-cap layer. Improvement in electromigration performance due to hydrogen has also been attributed to interfacial segregation of hydrogen and the reduction of defects by athermal annealing. Thus, the observed improvement in H\textsubscript{2} treated samples may have been contributed by formation of hydrides or reduction of Cu oxide with consequent better adhesion. The present XPS analysis clearly indicated that the H\textsubscript{2} plasma treatment also facilitates the formation of both Cu–N and Cu–Si bonds at the interface (Fig. 4-6), which directly improve the electromigration performance (Table I). Improvement due to silane treatment may be attributed to silicide formation on the Cu surface. 

![Figure 6. Deconvolution of Cu 2p\textsubscript{3/2} spectra (a) without treatment, (b) with NH\textsubscript{3}, (c) with H\textsubscript{2}, and (d) SiH\textsubscript{4} treatments.](image)

![Figure 8. Lognormal plot of failure times of (a) upper (M-2) layer and (b) lower (M-1) layer test structures with different surface treatments.](image)

Although there is a large amount of Cu–N bonds which present in NH\textsubscript{3} treated specimens, its electromigration reliability is comparable to the specimen without treatment. Terrace-ledge-kink (TLK) model has been put forward to explain the surface diffusion phenomena, where a continuous flux of adatoms on the surface is necessary. The kink sites are believed to be the source of the adatom flux because at the kink sites the transition to an adatom involves the breaking of the smallest
number of bonds. Therefore, the key to stop or retard the surface-interface electromigration in Cu interconnects is to reduce the number of kink sites or to increase the energy needed to dissociate Cu atoms from the kink sites. In the present study, the formation of Cu–N and Cu–Si bonds can both passivate the kink sites. However, it is expected that the Cu–Si bond is much stronger than the Cu–N bond. From the thermodynamic point of view, Cu–Si has a bond formation enthalpy around $-220 \text{ kJ/mol}$, whereas that for the Cu–N bond is around $-30 \text{ kJ/mol}$. Therefore, it is the formation of copper silicide that will enhance the EM lifetime more, which is the case for H$_2$ and SiH$_4$ treated specimens. The contribution of copper nitride to EM reliability is much less appreciable than that of copper silicide.

Microstructural changes arising from surface treatment cannot be completely ruled out, but this change and its effect on electromigration is likely to be less significant because the grain structure was stabilized due to post-Cu deposition anneal and TEM images (Fig. 12) showed bamboo-like grain structure with large grains.

The observed improvement in electromigration performance due to surface treatment supports Cu/dielectric cap interface dominated electromigration mechanism. Consider how Cu/dielectric cap interface modification affected electromigration in upper- and lower-layer dual-damascene structures. The different electromigration performance of upper and lower structures has been explained to be due to different electromigration mechanism in these structures. It is proposed that the location of maximum stress in case of upper-layer structures it is at the Cu in the cathode-end via, which is surrounded by Ta on all sides, while for lower-layer structures is at the Cu/dielectric interface near the cathode-end via bottom where void can be easily nucleated, leading to a shorter lifetime of lower-layer structures. However, in a recent study of electromigration mechanism in upper and lower layer structures using in situ scanning electron microscope (SEM) characterization technique, the electromigration mechanism in both the upper and lower-layer structures seems to be similar in that the Cu/dielectric interface facilitates the heterogeneous nucleation of voids and also provides a path for void movement. In both the structures, voids were found to be nucleated at the Cu/dielectric interface in the line, away from the via, and move along this interface towards the cathode end where they agglomerate to form a void and cause electrical opening of the via. These observations suggest that the electromigration performance of both upper and lower-layer structures can be improved by improving the Cu/dielectric cap interface. Improved electromigration performance of both upper and lower-layer structures with modification of Cu/dielectric interface due to surface treatments supports this.
mechanism. The failure times of lower-layer structures with silane treatment were found to significantly improve and the MTF was almost similar to upper-layer structures. This indicates that the electromigration performance of lower-layer structures, which have significantly lower failure times than upper-layer structures and can limit the overall electromigration reliability of dual-damascene structures, can be improved by surface treatments.

Conclusions

Surface treatment can be effectively used to improve overall electromigration reliability of dual-damascene Cu interconnects, and is compatible with the conventional damascene process. The observed effect on both the upper and lower-layer structure supports the Cu/dielectric cap interface dominated electromigration mechanism in both of these dual-damascene interconnect structures. Hydrogen plasma and silane treatments were found to yield the best improvement in electromigration performance. It is found that formation of Cu silicide prior to nitride formation could improve EM lifetime appreciably.

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