Stress in Copper Seed Layer Employing in the Copper Interconnection

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Chemical mechanical planarization (CMP) is important in the copper damascene process. A thick copper conductive layer has been deposited by electroplating on the sputtered copper seed layer on the barrier layer. When the tantalum nitride (TaN) barrier layer, which is known as a promising barrier layer for copper diffusion, is used, the copper layer peels easily during CMP. Slightly better adhesion strength is obtained in the Ta barrier layer. However, this layer is not always useful as a barrier layer. Therefore, a Ta/TaN bilayer has been used extensively as adhesion and barrier layers in this interconnection.

The barrier effect for copper diffusion has been studied for different barrier layers. Copper diffuses so deeply through grain boundary into polycrystalline barrier layers, such as in titanium nitride (TiN), Ta, and tantalum nitride (TaN) layer, that thick barrier layers, for instance, >20 nm thick, must be deposited. A lower resistance interconnection layer cannot be manufactured from a copper layer surrounded by a thick barrier layer. A lower resistance sheet can be attained in copper interconnection layers when thin microcrystalline or amorphous (a-)TaN and low silicon composition TaSiN barrier layers are used.

Agglomeration becomes a more serious problem in fine copper seed layers. Agglomeration largely affects peeling of the copper layer during CMP as well as the orientation of the Cu(111) layer. However, origin and details of the agglomeration have not been well understood. Recently, it was reported that the adhesion strength at the Cu/barrier layer is affected largely by the stress of copper layer. Correlation of the adhesion strength with the stress must be studied to solve the problem peeling which occurs frequently in the copper conductive layer. The adhesion strength at the Cu/barrier layers and the Cu orientation of copper layer, reduction of stress is important. Higher and high stresses are applied in the layer on TaN and Ta barrier layers. These layers can lead to poor adhesion strength. Much better adhesion strength can be accomplished in the layer on the TaSiN barrier layer. The surface changes to rough surfaces with annealing at 400°C in the layer deposited on TaN. The highly stressed layer changes to a low stress layer as a result of this agglomeration. However, a smooth surface is held in the low stress layer on the TaSiN barrier layer.

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Results and Discussion

After depositing a thin copper seed layer on different barrier layers, stress was observed quantitatively from the shift of the X-ray diffraction spectra. The following equation can be obtained by Bragg’s diffraction

\[ 2d \sin \theta = n\lambda \]  

where \( \theta \), \( n \), and \( \lambda \) are incident angle, refractive index, and wave length, respectively. Shift of the spectra, \( \Delta 2\theta \), can be obtained by differentiating this equation as

\[ \Delta 2\theta = 2 \tan \theta (\Delta d/d) \]  

where \( d \) and \( \Delta d \) are lattice constant and lattice distortion, respectively. Shift of the X-ray diffraction spectra can be determined quantitatively by this measurement. Because this shift is proportional to the lattice distortion ratio, \( \Delta d/d \), lattice distortion and the stress at the interface can be determined from this measurement.

A copper seed layer was deposited on different barrier layers. Spectrum shift, \( \Delta 2\theta \), was determined from the X-ray diffraction measurement for as-deposited copper layers. The observed spectra shifted slightly to the higher angle side from an angle of 43.295° in bulk copper given by ASTM. The observed spectrum shift, \( \Delta 2\theta \), of each copper seed layer is shown in Fig. 1. The spectrum shift is very different among these barrier layers. This result shows clearly that the stress can be controlled broadly by varying the barrier layers. The highest stress was obtained in a layer on CVD TiN layer. High stress was obtained in a-TaN and c-TaN barrier layers. This shift decreased to 0.85 when a Ta barrier layer was used. However, diffusion barrier performance is so poor in this layer Ta is not acceptable as a barrier layer. The shift of .2, decreased to 0.15 and the lowest stress was realized when a seed layer was deposited on a low silicon content TaSiN layer. Recently, it was found that the stress of a seed layer on the TaSiN barrier layer can be controlled by varying the Si and N compositions. Optimizations of these compositions are important in the manufacture of stress-free seed layers.

Empirically, peeling occurs frequently in the copper conductive layer deposited on the TaN barrier layer. However, this peeling does not occur as frequently in the layer on a Ta barrier layer. However, correlation of the adhesion strength with the stress has not been studied in multilevel copper interconnections. Adhesion strength at the copper seed layer/barrier layer was observed quantitatively by the Sebastian technique. Correlation of the adhesion strength with

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the stress given by $\Delta \theta$ is shown in Fig. 2 by closed circles, where $\Delta \theta$ was determined in Fig. 1. This figure shows clearly that adhesion strength is closely related with the stress of the seed layer and can be varied broadly with varying the stress. That is, the adhesion strength of the copper layer increased with decreasing stress. Higher and highest adhesion strengths were obtained in Ta and TaSiN barrier layers. This adhesion strength variation is consistent with the empirical data met in the CMP process for copper interconnection. The problem of such peeling may be solved if only a low stress copper seed layer can be deposited on a TaSiN barrier layer.

Agglomeration of a 10 nm thick copper seed layer was studied, where a-TaN barrier layer was used. This layer is a typical and promising barrier layer. Variation of the X-ray diffraction spectra for the Cu(111) with annealing at 400°C is shown in Fig. 3. A weak Cu(111) peak appeared at 45.423° in the as-deposited layer although it should appear as a strong peak at 43.295° in a stress-free copper layer as given by ASTM. This shift of the spectrum by 2.128° indicated the deposition of a highly stressed and weakly (111) oriented copper seed layer. This spectrum was separated into two spectra with an increase in annealing time to 10 min. A weak peak due to the low stress copper layer was observed at 43.295°. Spectrum for the stressed layer still appeared at 45.423° as seen in Fig. 3. This spectrum change indicated that the layer stress is reduced with this 10 min annealing and also that a highly stressed layer still exists at the surface. When annealing time increased to 20 min, the spectrum at 45.423° due to the stressed copper layer disappeared completely and the spectrum at 43.295° changed to a strong peak. A small peak of (200) also appeared at 50.7°. These spectrum changes indicated clearly that the stress can be released sufficiently with this long time annealing. This layer is regarded as stress free.

Such stress relaxation and formation of a stress-free copper layer may be achieved by agglomeration. Agglomeration of the copper seed layer is a serious problem in the copper interconnection. The relationship between stress and the formation of agglomeration was studied. Variation of surface morphology in the copper seed layer with an annealing time at 400°C was observed by the SEM. Variation of the surface morphologies with this annealing is shown in Fig. 4. The amount of shift determined in Fig. 3 is shown numerically at the top of these photographs. A very smooth surface was obtained in the as-deposited copper layer because greater stress was applied at the interface as given in Fig. 1 and 3. When annealing time was increased to 10 min, agglomeration occurred just at the
interface. However, the surface feature was invariable and remained smooth as seen in Fig. 4b. This morphological change and X-ray diffraction measurements showed that agglomeration appeared just at the interface with an α-TaN layer. This agglomeration region was broadened and the layer changed to a discontinuous layer over the whole area when annealing time was increased to 20 min as seen in Fig. 4c. It must be noted from the data in Fig. 3 and 4 that the stress-free thin copper layer is formed as a result of the formation of agglomeration.

Conclusions

1. Stress of a thin copper seed layer can be controlled broadly with varying the barrier layer used as a substrate layer. Higher stress was applied in the layer on TiN and c-TaN barrier layers. A slightly lower stress layer can be deposited on c-TaN and Ta layers. Lowest stress was attained when the layer was deposited on a low Si composition TaSiN barrier layer.

2. Stress was reduced by annealing at 400°C even in a highly stressed seed layer. This stress reduction is caused by the formation of agglomeration.

3. Adhesion strength at the Cu/barrier layer is closely related with the stress at the interface. Very low adhesion strength was attained when TaN was the barrier layer. Slightly better adhesion was attained in the Ta barrier layer employed.

4. Better diffusion barrier performance and better adhesion strength were attained when a low Si content TaSiN layer was employed instead of a Ta/TaN barrier layer.

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