A study on ultra thin and continuous CVD-Cu film for ULSI Cu interconnect

(ULSI 多層配線用極薄連続 CVD-Cu 膜に関する研究)

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1. Introduction

The demand for high functionality, low power consumption, and high speed of ultra-large-scale integration (ULSI) devices has been achieved by reducing the feature size and increasing clock frequencies. Increasing circuit speed faced the limitation due to the resistance-capacitance (RC) delays in interconnects. Moreover, the decrease in cross-sectional area and the increase in frequency of the interconnect line cause the increase of current density, which results in electromigration (EM) failure in interconnect. Thus, lower resistivity and higher melting point interconnect metal is required to decrease RC delay and to increase EM resistance, which are achieved by replacing Al with Cu. However, Cu interconnects do not show a good EM resistance as expected due to its poor adhesion property at the interface where is the main EM path of current Cu interconnects. Inserting an adhesion promoter, glue layer, between Cu and barrier is an effective method to increase the adhesion at the interface and EM resistance as well. However, the study on glue layer element is not investigated systematically. In this study, thus, I investigate selection of the best glue layer element for highly reliable future Cu interconnects.

Beside the issue of glue layer, the synthesis of thin CVD Cu is also significant subject for future Cu interconnects, because the current Cu filling method, which consists of sputtering seed layer deposition and electroplating, faces severe limitation. Namely, the seed layer deposited by sputtering has poor step coverage, thus it should be changed to conformal deposition method, such as CVD. To cope with the scaling down the Cu interconnect, ultra thin and continuous CVD Cu seed layer (~10 nm) is required. However, current CVD technology cannot fabricate Cu seed layer with thickness below 100 nm due to poor Cu wettability of the under-layer and island growth of metallic CVD Cu, which must be solved to deposit ultra thin and continuous CVD Cu seed layer. Thus, the best glue layer having the best Cu wettability is evaluated as new under-layer, and Cu oxide deposition and its reduction is suggested, because Cu oxide has better morphology than metallic Cu due to its good wettability caused by lower surface energy of Cu oxide.

Summarizing the main topics of this dissertation, it is focused on the selection of glue layer with the best adhesion to Cu, and the fabrication of ultra thin CVD Cu seed layer.

2. Result and Discussion

2.1 Material Design for Highly Reliable Cu Interconnect

EM resistance of ULSI Cu interconnect can be improved by inserting adhesion promoter between Cu and diffusion barrier. Metallurgical survey is accomplished to select the element with a good Cu adhesion property. To introduce an element as interconnect material, it should have a low resistivity and it dose not react with Cu to avoid increasing resistance of Cu interconnect. Ru, Os, Mo, W, and Ta satisfy the above conditions. The Cu adhesion property of these elements is estimated by lattice misfit concept, i.e., the hexagonal closed packed (hcp) element having good matching interface with face centered cubic (fcc) Cu is expected to show better Cu adhesion property than that of body centered cubic (bcc) elements. Cu adhesion property is experimentally examined and compared hcp elements (Ru, Os) to bcc elements (Mo, Ta). Ru and Os which have lower lattice misfit values show better adhesion property than bcc elements having relatively higher lattice misfit value. Among these elements, Ru has the best Cu adhesion property and thus it can be an optimum glue layer element for highly reliable Cu interconnects. As the optimization of Ru preparing condition, the adhesion property of Cu is compared on Ru having different crystal orientation, i.e. Ru(001) having good matching with Cu(111) and Ru(100) having poor matching with Cu. As expected by lattice misfit concept, Ru(001) has better adhesion property of Cu than (100) crystal orientation of Ru. Thus, Ru layer having (001) orientation is the best glue layer for highly reliable Cu interconnect.

2.2 Cu Seed Layer Deposition on Ru Under-layer by Chemical Vapor Deposition

Thin and smooth CVD seed layer is required for future ULSI Cu interconnects. The most effective parameter on the morphology of CVD Cu is the good Cu wettability of under-layer. Ru is selected as the best glue layer, which has a good Cu wettability. Considering the integration, CVD Cu seed layer have to be deposited on Ru glue layer, thus the deposition behavior of CVD Cu on Ru is very important for evaluating its application. In this chapter, the deposition behavior of CVD Cu on Ru under-layer is investigated, which is compared with that on Ta under-layer in the viewpoint of morphology and adhesion property. For thin and continuous seed layer deposition, small and high density of nuclei is favorable, and it can be achieved by optimizing process parameters and introduction of Ru under-layer. At low temperature (90^{o}C), as far as maintaining reasonable deposition rate, small nuclei size is obtained, and CVD Cu films on Ru show higher nuclei density than that on Ta, which results in a thin and smooth morphology of CVD Cu film. High source concentration also improved the nucleation density of CVD Cu at low temperature. About 20 nm of smooth and continuous CVD Cu seed layer is deposited at 90^{o}C and high source concentration condition on Ru. CVD Cu films on Ta are peeled off at overall the deposition conditions, whereas that on Ru shows a good adhesion property. Fluorine known as degrading adhesion of CVD Cu film is not detected at the interface between Ru and CVD Cu, which result in the good Cu adhesion property. Introducing Ru under-layer and optimized deposition conditions enable thin and smooth

CVD Cu seed layer deposition for future Cu interconnects. However, the morphology of CVD Cu becomes rough by changing the orientation and crystallinity of Ru. Especially, as a promising candidate of Ru deposition method, thin ALD Ru under-layer having poor crystallinity shows poor morphology of CVD Cu. Thus, strong (001) oriented ALD Ru and more robust CVD process are required for future ULSI interconnect.

2.3 Cu Seed Layer Deposition by Cu Oxide Deposition and its Reduction Method

Cu MOCVD has been studied as a method of conformal seed layer deposition. However, because of a poor nucleation behavior of CVD Cu, a rough surface morphology is a main drawback of this technology. To improve the nucleation behavior of CVD Cu, Cu oxide deposition is suggested, because it has better wettability due to its lower surface energy than metallic Cu. In this chapter, a thin CVD Cu seed layer deposition using a Cu oxide deposition and its reduction is investigated. To apply this process as a seed layer deposition, two main issues have to be solved. i.e., Cu oxide deposition and reduction process require very high process temperature (~300°C), and the barrier surface is oxidized during Cu oxide deposition, which causes the increase of contact resistance and the degradation of reliability. To decrease deposition temperature, a Cu oxide is deposited with Cu(I) precursor, having a low process temperature, and H_2O_2. Using these precursors, smooth Cu oxide is deposited at 100°C not only on (001)Ru but also on ALD Ru, which means that Cu oxide deposition is less sensitive to the under-layer. Formic acid reduces this oxide film below 100°C. The barrier oxidation can be prevented using the Ru under-layer that is easily reduced during reduction of the Cu oxide. One more important role of Ru under-layer is maintaining a good surface morphology of reduced Cu film due to its good Cu wettability. This result suggests that Cu oxide deposition and its reduction on Ru is a promising candidate for ultra thin CVD Cu seed layer deposition.

3. Conclusion

The main issues of future Cu interconnect, poor Cu adhesion of barrier and thin and smooth CVD seed layer, are investigated. The element having the best Cu adhesion property is selected using lattice misfit concept, and the thin Cu CVD seed layers are deposited by metallic Cu or Cu oxide deposition and its reduction method.

Ru(001) shows the best Cu adhesion property due to good matching with Cu(111) plane, which improves the morphology of CVD Cu. However, metallic Cu CVD has limitations in scaling down, and it is sensitive to the crystal orientation of Ru. This problem is solved by Cu oxide deposition and its reduction method, which can deposit about 10 nm thin and continuous CVD Cu seed layer even on ALD Ru that has a poor Cu wettability. Introducing Ru as glue layer and developing of Cu oxide deposition and its reduction method can give a solution for the reliability and process issues of future ULSI Cu interconnect