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Effective Cu surface pre-treatment for high-reliable 22 nm-node Cu dual damascene interconnects with high plasma resistant ultra low-*k* dielectric (*k* = 2.2)

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ABSTRACT

Effects of Cu surface treatment (NH_3 plasma irradiation) before the cap dielectric deposition on low-*k* surface damage and Cu surface cleaning were systematically investigated. From the blanket film surface damage evaluations of porous low-*k* film with high carbon content and the oxygen removal on blanket Cu film after chemical mechanical polishing (CMP), the optimized NH_3 plasma condition such as high RF power and high pressure exhibited the high efficiency for oxygen removal from the Cu surface without increasing the *k*-value of low-*k* film. The low-*k*/Cu interconnect (line/space = 40/40 nm) for 22 nm-node with the high plasma resistant low-*k* film and the optimized Cu surface treatment showed longer electromigration lifetime without large degradation of RC performance.

1. Introduction

The porous low dielectric constant (*k*) materials have been extensively implemented in scaled-down ULSIs to reduce signal propagation delay and power consumption [1,2]. For further reduction of *k*-value, the process damage of low-*k* films is one of the most serious concerns to improve the interconnect performance and reliability. Fig. 1 shows the schematic diagram of the dual damascene (DD) interconnect structure and the main region of the process damage. During the fabrication of the DD interconnect, the process damages mainly occur at the low-*k* surfaces adjacent to the different materials such as trench top surface (low-*k*/cap), sidewalls of trench and via (low-*k*/barrier-metal), and trench bottom (low-*k*/barrier-metal). The low-*k* damage repair [3] and damage layer elimination [4] processes are promising ways to suppress the capacitance increase by the side-wall and trench bottom damages induced by the plasma processes such as etching and ashing. However, it is difficult to modify the low-*k* surface damages after Cu surface pre-treatment, because the cleaned Cu surface adjacent to the low-*k* surface needs to be maintained throughout until following dielectric cap deposition, as shown in Fig. 1. The Cu surface treatment with NH_3 plasma is effective to remove the oxygen from the Cu surface and to improve the interconnect reliability such as electro-migration (EM) [5], but the low-*k* film surface is simultaneously damaged by plasma irradiations. Thus, it is quite important to optimize the NH_3 plasma condition with good balance between the Cu surface cleaning efficiency and the low-*k* damage resistance, as well as introducing the robust low-*k* material against the plasma damage.

In this study, the Cu surface treatment condition was optimized by controlling NH_3 plasma parameters, using high plasma resistant low-*k* film (*k* = 2.2), from the view points of low-*k* surface damage and deoxidation of Cu surface. Using the optimized Cu surface treatment, we also successfully demonstrated the high-reliable and high-performance low-*k*/Cu interconnects with 80 nm-pitch for 22 nm-node.

2. Experimental

The porous low-*k* films were deposited by plasma-enhanced chemical vapor deposition (PECVD). We used the porous low-*k* film (*k* = 2.2) with high carbon content, using second skeletal carbosilane precursor to introduce much hydrocarbon, in addition to conventional basic precursors of diethoxymethylsilane (DEMS) for SiCOH skeleton formation and porogen for pore insertion [6]. All films were cured with UV light at 385 °C. The carbon content was varied by adding a second skeletal precursor to incorporate

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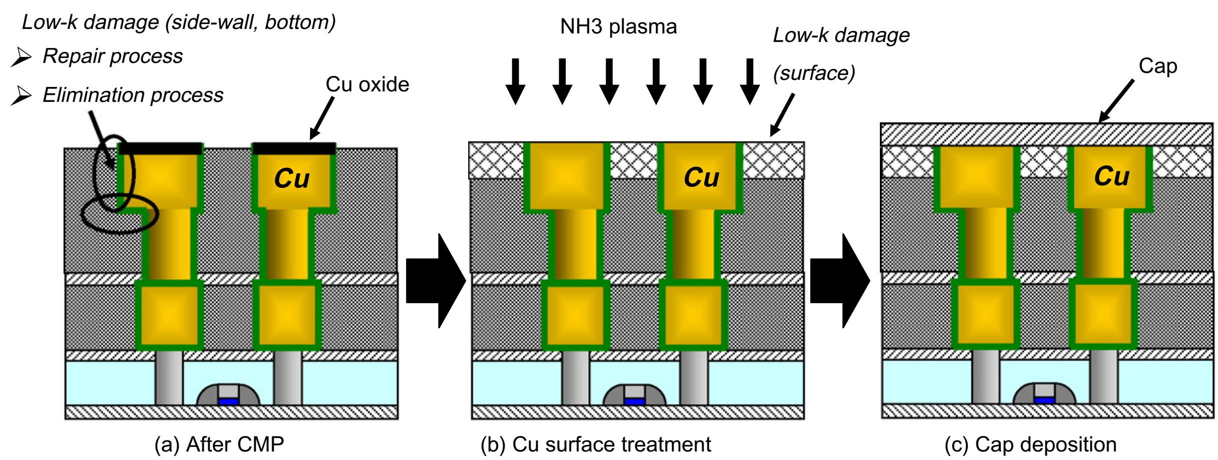

Fig. 1. Schematic diagram of dual damascene interconnect structure and process flow of in situ Cu surface treatment.

carbon bonding with the silicon [6]. The carbon content and porosity of the low-*k* film used in this study were 36% and 27%, respectively. The *k*-value was measured by conventional capacitance and voltage (C–V) measurement at 150 °C to minimize the physisorption of moisture and other ambient gases, using metal–insulator–semiconductor (MIS) structures fabricated by evaporating aluminum. The surface chemical composition of the low-*k* and Cu blanket films was measured by time-of-flight secondary ion mass spectrometry (TOF-SIMS). The damaged layer analysis of the low-*k* films was also performed by X-ray reflectivity (XRR). The adhesion strength at the interface between cap dielectric and Cu was evaluated by four point bending test.

Table 1 shows three conditions of NH_3 plasma treatment process. Condition #1 indicates low RF power (225 W) and high pressure (3 Torr). Condition #2 was controlled to be higher power (550 W) than that of condition #1. In addition, we adjusted condition #3 to lower pressure (1.6 Torr) compared with condition #2. The NH_3 plasma treatment for all conditions were performed at 350 °C for various treatment times (0–20 s).

The low-*k*/Cu DD interconnect (L/S = 40/40 nm) for 22 nm-node with the high plasma resistant low-*k* film and the optimized Cu surface treatment was fabricated using via first etching process [7]. To verify the effects of NH_3 plasma treatment on the low-*k* damage suppression and Cu surface cleaning, the interconnect capacitance and the EM performances were evaluated for various NH_3 plasma conditions.

3. Results and discussion

3.1. Low-k surface properties

Fig. 2 shows the plasma induced damage (PID) as a function of carbon content in the low-*k* film. The PID was characterized by measuring the relative thickness loss after dilute HF (DHF) wet etching for the low-*k* films exposed by mixing gas plasma of argon and oxygen. The low-*k* materials with higher carbon content were found to be more resistant to plasma induced damage than low carbon films with the same *k*-value. These results are consistent with previous works about plasma and photon irradiations onto various low-*k* materials [6,8,9]. Thus, the high carbon film with additional second skeletal carbosilane precursor results in the strong resistance for plasma induced damages in comparison with conventional low carbon films.

Table 1
Three conditions of NH_3 plasma treatment process used in this study.

NH_3 plasma condition	RF Power (W)	Pressure (Torr)	Temperature (°C)	Time (s)
#1 (Low-power)	225	3.0	350	0–20
#2 (High-power)	550	3.0	350	0–20
#3 (High-power, low-press)	550	1.6	350	0–20

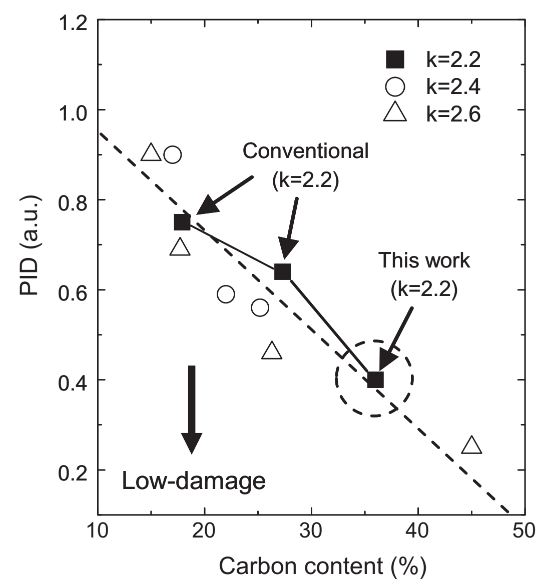

Fig. 2. Plasma induced damage (PID) as a function of carbon content for various *k*-value (k = 2.2, 2.4, and 2.6). PID means relative thickness of damaged layer after plasma exposure of argon and oxygen.

Fig. 3 shows *k*-value increase as a function of treatment time for three types of NH_3 plasma conditions. There was no significant increase in *k*-value below 5 s except for condition #3. At high pressure of 3 Torr, the low-*k* damage was less sensitive to RF power, especially for treatment time less than 5 s. The surface damaged layer after NH_3 plasma irradiation were also evaluated by TOF-SIMS and XRR. The TOF-SIMS depth profile showed a carbon-depleted region containing Si and O around only the top surface of the film. The surface oxide-like layer tended to be deeper with increasing the NH_3 treatment time. Regarding the XRR analysis, fitting accuracy of two-layer model (surface-layer and bulk) against the experimental data was much better than that of single layer model, indicating the existence of the surface damaged layer. In