TDDB Reliability Improvement in Cu Damascene by using a Bilayer-Structured PECVD SiC Dielectric Barrier

C. C. Chiang and M. C. Chen
Department of Electronics Engineering, National Chiao-Tung University
1001 Ta Hsueh Road, Hsinchu 300, **Taiwan**
Z. C. Wu, L. J. Li, S. M. Jang, C. H. Yu, and M. S. Liang
Taiwan Semiconductor Manufacturing Company
No.9, Creation Rd. I, Science-Based Industrial Park Hsinchu, **Taiwan**

Abstract

This work investigates the thermal stability and barrier characteristics of two species of silicon carbide dielectric films, α-SiCN with a dielectric constant of 4.9 and α-SiC with a dielectric constant of 3.8. The TDDB lifetime of Cu damascene metallization structure is greatly improved by using a α-SiCN/α-SiC bilayer dielectric stack as the etching stop layer (ESL). This improvement is presumably due to the α-SiC dielectric's lower leakage current, absence of nitridation on Cu surface, and better adhesion on Cu as well as OSG intermetal dielectric (IMD), though the α-SiC film has a very slow deposition rate. We believe that the α-SiCN/α-SiC bilayer dielectric is a favorable combination for the ESL because α-SiCN can protect α-SiC from plasma attack during the photoresist stripping.

Introduction

As the device dimensions continuously shrink, the RC time delay of the interconnect system becomes one of the most important limitation factors to the integrated circuits performance. In order to minimize the signal propagation delay, it is inevitable to use low dielectric constant materials as the inter-layer and intra-layer dielectrics (ILD). While many low-k ($k<3.0$) materials have been used as ILDs, the silicon nitride with a high dielectric constant ($k>7.0$) is still the primary candidate for the ESL required in copper damascene structures. Thus, it is desirable to replace silicon nitride by new materials with lower dielectric constants to further reduce the effective dielectric constant of the Cu interconnect system. In recent years, increasing interest has been focused on the study of low stress and thermally stable low-k amorphous silicon carbide-based (α-SiC:H) films deposited by PECVD using organosilicon gases [1-2]. In this work, we investigate the thermal stability and barrier characteristics of α-SiC:H dielectric films ($k<5$). It turns out that the TDDB lifetime of Cu damascene metallization is greatly improved by using a bilayer-structured SiC dielectric barrier.

Experimental

Two species of PECVD amorphous silicon carbide with k values less than 5 are investigated with respect to the thermal stability and barrier characteristics. The α-SiC:H films, designated as SC1 (α-SiCN) and SC2 (α-SiC), were deposited on p-type, (100)-oriented Si wafers to a thickness of 50 nm. Metal electrode (Cu or Al) was deposited on the silicon carbide films to construct the metal-insulator-semiconductor (MIS) capacitor structure. For the Cu-electrode MIS capacitors, a Cu layer of 200 nm thickness was sputter deposited on the α-SiC:H films, followed by a reactive sputter deposition of a 50 nm thick TaN layer on the Cu surface for the purpose of preventing oxidation of Cu electrode in the subsequent thermal process. Al-electrode samples were also prepared by depositing 500 nm thick Al layers directly on the α-SiC:H dielectric surfaces. The TaN/Cu- and Al-electrode MIS capacitors were then annealed at 400°C for 30 min in an N_2 ambient before any electrical measurements. Cu damascene structures were constructed for the TDDB reliability study. Fig. 1 shows the comb1/serpentine/comb2 test structure and cross-sectional TEM micrograph of the Cu damascene structure employed in this study. A PECVD OSG (α-SiCO:H) film was first deposited to serve as the IMD. After patterning of 0.20 μm trenches in the OSG dielectric, the damascene Cu features were electrochemically deposited on a 30 nm thick TaN barrier. Following the Cu CMP, either a SC1 (50 nm) single layer dielectric or a SC1 (25 nm)/SC2 (25 nm) bilayer dielectric stack was prepared as the ESL. The Cu damascene structure with a SC2 single layer ESL was not prepared in this study because of the very slow deposition rate of SC2 dielectric. Finally, the damascene Cu structure was passivated with a USG capping layer of 400 nm thickness.

An HP4145B semiconductor parameter analyzer was used to measure the dielectric leakage current and provide bias for the bias-temperature-stress (BTS). The thickness of films was measured using an N&K analyzer at 633 nm wavelength. Fourier Transform Infrared Spectroscopy (FTIR) was used to analyze the chemical bonding of the dielectrics. The adhesion of films was measured using a 4-point bending technique [3]. The k value of dielectrics was determined by the

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maximum capacitance of the Al-gated MIS capacitors measured at 1MHz using a Keithley Package 82 system.

Results and Discussion

Table 1 shows some basic data of the α-SiC:H dielectrics. Fig. 2 illustrates the FTIR spectra, and Fig. 3 shows the film thickness shrinkage as well as dielectric constant as a function of annealing temperature (for 30 min in an N_2 ambient). Notably, the deposition rate of SC2, which contains no nitrogen at all, is much slower than that of SC1. The SC2 film has a dielectric constant of about 3.8, while the nitrogen containing SC1 film has a higher dielectric constant of about 4.9, presumably due to the polarization contribution from nitrogen. The substantial increase in thickness shrinkage and dielectric constant for both SC1 and SC2 films at temperatures above 500°C is attributed to the outgassing of methyl group, resulting in the decrease of $Si\text{-}CH_3$, C-H, and Si-H peak heights, as shown in the FTIR spectra.

Fig. 4 shows the leakage current density of Al/SC1/Si and Al/SC2/Si MIS capacitors measured at various temperatures. The time dependent dielectric breakdown (TDDB) was measured on the TaN/Cu-electrode SC1 (50 nm), SC2 (50 nm), and SCB (25 nm SC1/25 nm SC2) MIS samples at 200°C under a bias stress of 1 MV/cm. Fig. 5 illustrates the leakage current transient during the BTS and the instantaneous leakage current density versus applied electric field (in accumulation mode) before and after the BTS. All the samples remained stable under the BTS up to at least 15 hrs. This implies that all the dielectric bulk films were capable of preventing Cu permeation.

Fig. 6 illustrates the results of leakage current measurements and breakdown field statistics for the Cu damascene metallization structures with SC1 as well as SCB as the ESL. The breakdown field is defined as the field strength such that the Cu damascene structure's leakage current between comb1/comb2 (grounded) and serpentine (positive biased) exceeds 1mA. The Cu damascene structure with a SCB bilayer ESL exhibits a much lower leakage current and higher breakdown field than that with a SC1 single layer ESL. The results of TDDB measured on the Cu damascene structures with SC1 and SCB ESLs at 200°C under a bias stress of 2 MV/cm are illustrated in Fig. 7, while the time-to-breakdown of the damascene structures is shown in Fig. 8. The damascene structure with a SCB bilayer ESL has a higher value of TDDB lifetime as well as time-to-breakdown compared with the structure using a SC1 single layer ESL. All these observations are attributed to the lower leakage current of SC2 dielectric bulk film (Fig. 4) since both dielectric bulk films were capable of preventing Cu permeation (Fig. 5). In addition, the adhesion strength of SC2/Cu and SC2/OSG interfaces is superior to that of SC1/Cu and SC1/OSG interfaces, as shown in Table 2. A nitridation of Cu surface (CuN_x) was observed in SC1/Cu but not in SC2/Cu by XPS (not shown). The ionized Cu atoms require lower activation energy for diffusion [4] and thus degrade the TDDB reliability of Cu damascene structure. Since the SC2 dielectric has a very slow deposition rate, we believe that the SC1/SC2 bilayer dielectric is a favorable combination for the ESL because the nitrogen containing SC1 film with the SiN_x compound can protect the SC2 film from plasma attack during the photoresist ashing process [5].

Conclusion

The TDDB lifetime of Cu damascene metallization structure is greatly improved by using a α-SiCN/α-SiC bilayer dielectric stack as the ESL. This improvement is attributed to the α-SiC dielectric's lower leakage current, absence of nitridation on Cu surface, and better adhesion on Cu as well as OSG IMD, though the α-SiC film has a very slow deposition rate. We believe that the α-SiCN/α-SiC bilayer dielectric is a favorable combination for the ESL because α-SiCN can protect α-SiC from plasma attack during the photoresist stripping.

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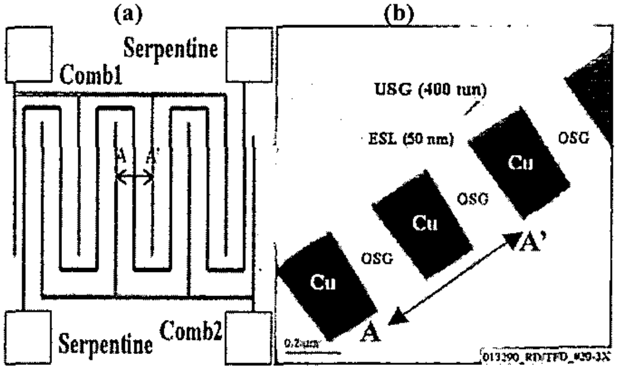

Fig. 1 (a) Schematic diagram of comb1/serpentine/comb2 test structure and (b) cross-sectional TEM of the Cu damascene structure.

Table. 1 Some basic data of α-SiC:H dielectrics.

Film Properties	SC1	SC2
Structure	α-SiC:N	α-SiC
(n,k)@633 nm	(1.90,0)	(1.85,0)
Dielectric Constant @0.1 MHz	4.5-5.0	3.5-4.0
Deposition Rate (A/min)	1760	26

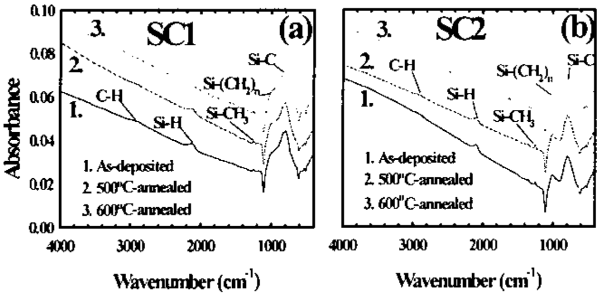

Fig. 2. FTIR spectra for two species of PECVD α-SiC:H dielectrics (a) SC1 and (b) SC2.

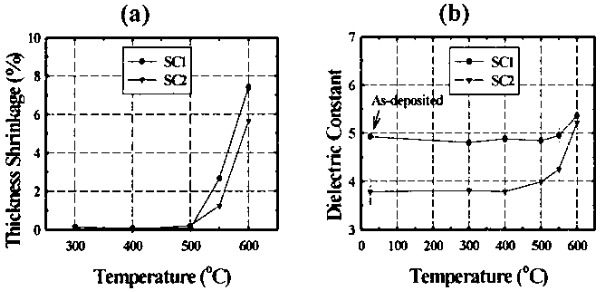

Fig. 3. (a) Thickness shrinkage and (b) dielectric constant vs. annealing temperature for two species of PECVD α-SiC:H dielectrics.

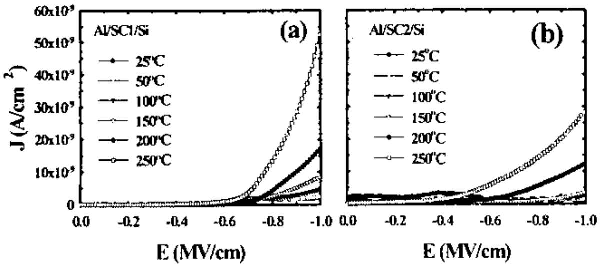

Fig. 4. Current density vs. electric field, measured at various temperatures, for (a) Al/SC1/Si and (b) Al/SC2/Si MIS capacitors.

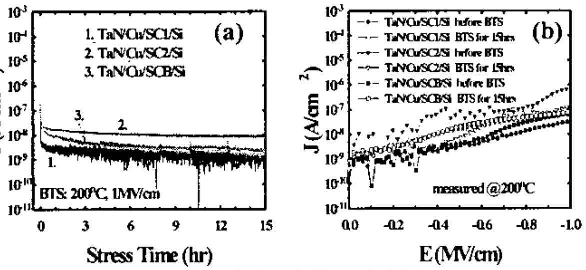

Fig. 5. (a) Current transient during BTS and (b) instantaneous current density vs. electric field before and after BTS (200°C and 1MV/cm) for TaN/Cu/SC1/Si, TaN/Cu/SC2/Si, and TaN/Cu/SCB/Si MIS capacitors.

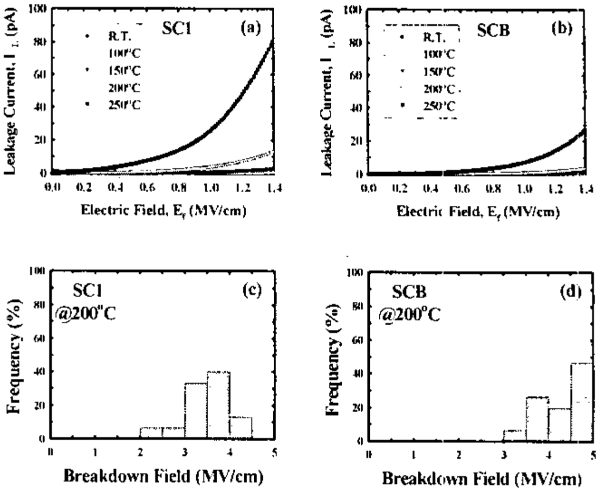

Fig. 6. Leakage current vs. electric field, measured at various temperatures, for Cu damascene metallization structure with (a) SC1 and (b) SCB ESL; histogram of breakdown field for the Cu damascene metallization structure with (c) SC1 and (d) SCB ESL.

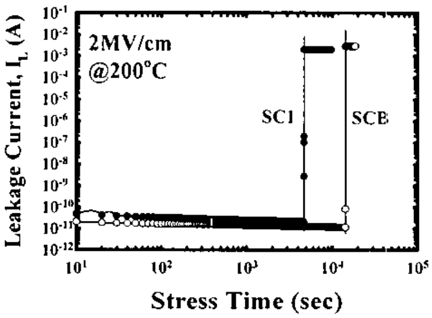

Fig. 7. Current transient during BTS (2MV/cm at 200°C) for Cu damascene structures with SC1 and SCB ESLs.

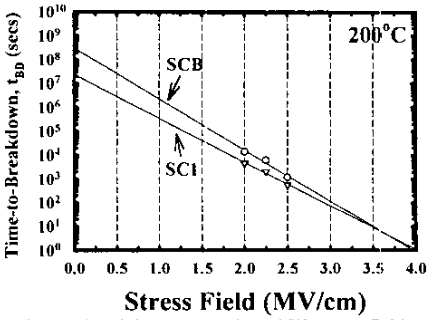

Fig. 8. Time-to-breakdown vs. various BTS stress fields at 200°C for Cu damascene structures with SC1 and SCB ESLs.

Table. 2 Adhesion strength of α-SiC:H dielectrics/Cu and α-SiC:H dielectrics/OSG interfaces.

Film Scheme	Adhesion Gc (J/m²)
Si/PE-OX/TaN/Cu/SC1	2.76
Si/PE-OX/TaN/Cu/SC2	8.44
Si/PE-OX/SiN/OSG/SC1	4.44
Si/PE-OX/SiN/OSG/SC2	9.34