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Effect of moisture on electrical properties and reliability of low dielectric constant materials

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A B S T R A C T

The effect of absorbed moisture on the electrical characteristics and reliability of low dielectric constant materials (low-*k*) was investigated in this study. The experimental results reveal that porous low-*k* dielectrics absorb more moisture than dense low-*k* dielectrics. This absorbed moisture degrades the electrical performance and reliability of both classes of low-*k* dielectrics. Annealing at a higher temperature of 400 °C is required to decompose the physically-adsorbed moisture and thereby restore reliability performance. However, the chemically-adsorbed moisture seems to be difficult to remove by annealing at 400 °C, causing a degraded TDDB performance.

1. Introduction

Low-*k* materials with dielectric constant (*k*) less than 4 as an interlayer dielectric with copper (Cu) interconnects displays significant advantages for interconnect resistance–capacitance (RC) delay improvement, crosstalk-noise minimization, and power consumption reduction for the continuous scaling of advanced integrated circuits [1–4]. Cu interconnects were adopted to replace conventional aluminum (Al) lines to reduce the resistance by about 30% [5]. The low *k* materials which incorporate low polarizability Si–F or Si–C bonds replaces Si–O bonds can reduce the dielectric constant to as low as 2.8, which is benefit for the capacitance between Cu interconnects reduction [6,7].

To further reach the desired reduction in RC delay for 32 technology node and beyond, low-*k* materials with *k* value of 2.5 or lower is required according to "International Technology Roadmap for Semiconductors" [8]. To obtain the low-*k* materials with a lower *k* value, the common strategy is introducing the porogen into the film and then the porogen is removed by thermal treatment or ultraviolet (UV) light radiation to produce the empty pore. The *k* value of the produced porous low-*k* materials can be further reduce to below 2.8, depending on the porosity of the film because the relative permittivity of empty pore is about 1.0 [9–11]. However, the integration of the porous low-*k* materials into Cu interconnects is extremely challenging because various technological process steps such as polymer removal, electrochemical plating, and chemical mechanical polish [12–14]. In these processes, low-*k* materials have to deal with the moisture and may induce water uptake. Moreover, the adsorbing amount becomes significant for the porous low-*k* materials due to the existence of open pores at the surface. Therefore, it is of importance to study the influence of moisture on the properties of low-*k* dielectrics.

This study investigated the impact of moisture on the physical and electrical properties as well as the reliability of low-*k* dielectrics. Different low-*k* dielectrics with and without porogen were tested in order to find out the moisture adsorption mechanism. The relationship between the moisture content of low-*k* material and the dielectric reliability was also studied.

2. Experiments

The as-deposited porous low-*k* material is a SiCOH film, deposited on a *p*-type (100) silicon substrates by plasma-enhanced chemical vapor deposition. The porous low-*k* dielectrics were deposited from diethoxymethylsilane and alpha-terpiene as a matrix and porogen precursor, respectively. A small amount of oxygen was also introduced as an oxidant. The deposition temperature, pressure, and power were 300 °C, 7.5 torr, and 600 W, respectively. After deposition, UV curing with 200–450 nm wavelength was

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performed to remove the organic porogen. The dense low-*k* dielectrics were also deposited in the same system without introducing porogen precursor. The resulting thickness is about 300 nm. The dielectric constants are ~2.54 and 3.02 for the porous and dense low-*k* materials.

For the moisture reliability test, the porous and dense low-*k* materials (blanket wafer) were immersed in humidity system of 85% humidity at 25 °C and 85 °C for 8–168 h. The chemical structure of low-*k* materials before and after moisture test was investigated by Fourier transform infrared spectroscopy (FT-IR) (Bio-Rad Win-IR PRO). Al metallization with 120 nm thick were thermally evaporated on the low-*k* dielectric films through the showdown mask to produce Metal–insulator–silicon (MIS) structure (Al/low-*k*/p-Si), as shown in Fig. 1, to measure electrical properties. The dielectric constant (k) was measured at 100 Hz. The current–voltage (I–V) and dielectric breakdown measurements were performed at room temperature (25 °C). Electromigration (EM) test structure of 250 μm length and 0.1 μm width was fabricated using Cu double-layered dual damascene interconnect. More details on test structure fabrication and EM characterization can be found elsewhere [15].

3. Results and discussion

Fig. 2(a) presents the FT-IR absorption spectra of porous low-*k* dielectrics before and after moisture treatment. As shown, absorption bands resulting from Si–OH bonds at 3200–3400 cm^{-1} are observed after moisture treatment, and the intensity of the Si–OH bonds increased with moisture immersion time, as shown in the inset in Fig. 2(a). To further compare the uptake of moisture by dense and porous low-*k* dielectrics, Fig. 2(b) plots the dependence of the intensity of the signals from the Si–OH bonds on the moisture immersion time for both classes of low-*k* dielectrics. The vertical axis represents the peak intensities of Si-OH bonds normalized to those of Si–O–Si bonds in the FT-IR spectrum. The peak intensities of Si–OH and Si–O–Si bonds were calculated from the peak area. As indicated, the peak intensity of Si–OH bonds increases with the duration of exposure to moisture and reaches saturation after 24 h of exposure. Moreover, porous low-*k* dielectrics show a higher moisture-uptake behavior than dense low-*k* dielectrics, indicating that the pores in the porous low-*k* films contribute to the uptake of moisture. For both classes of low-*k* dielectrics, more moisture is taken up at 85 °C than at 25 °C. Therefore, moisture treatment at 85% humidity and 85 °C was performed in this study.

Water contact angle (WCA) measurements were performed to evaluate the hydrophilization of low-*k* films after the moisture

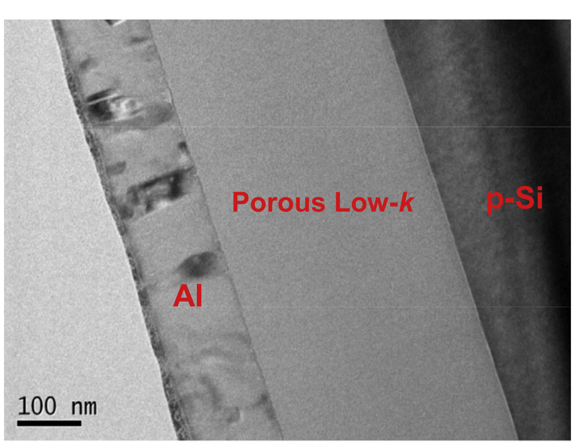

Fig. 1. Image of Al/porous low-*k*/p-Si stacked structure.

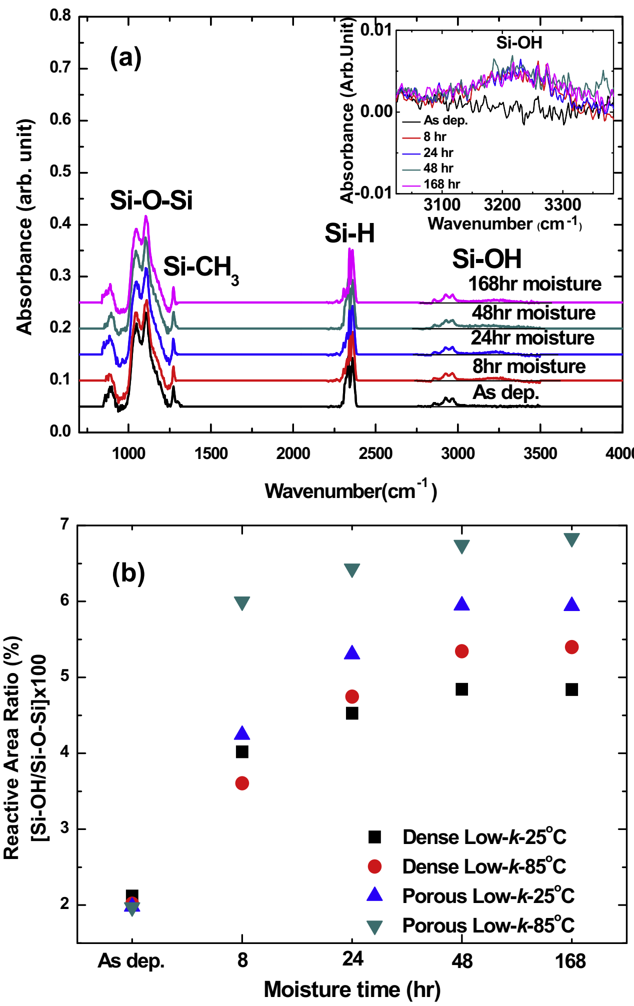

Fig. 2. (a) FT-IR spectra of low-k films after various moisture immersion times. (b) Relative Si–OH bonding absorbance intensity.

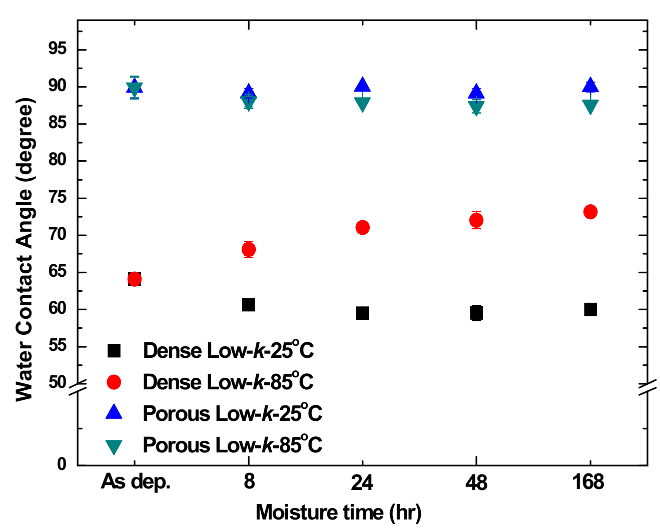

Fig. 3. Water contact angle of low-*k* films after various moisture immersion times.

test. The result is shown in Fig. 3. For as-deposited low-*k* dielectrics, porous low-*k* films had a larger WCA (~90°) than dense low-*k* dielectrics, indicating that porous low-*k* films were