ARTICLE IN PRESS

Thin Solid Films xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Comparison of O_2 plasma treatment on porous low dielectric constant material at sidewall and bottom of trench structure

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ARTICLE INFO

Keywords:
Low dielectric constant
Porous dielectric
O_2 plasma
Trench
Reliability
Time-dependent-dielectric-breakdown

ABSTRACT

The degradation induced by oxygen (O_2) plasma irradiation to the porous SiCOH materials with a dielectric constant of 2.56 (porous low-*k*) has been investigated in this study. The plasma damage on porous low-*k* films at the sidewall and bottom of the trench structure was compared by the design of a simple trench structure. Experimental results indicated that O_2 plasma irradiation degrades the electrical characteristics and reliability of porous low-*k* films at the sidewall and bottom of a trench structure. Porous low-*k* films at the bottom of the trench structure suffer more from O_2 plasma irradiation than those at the sidewall. As the width of the trench structure is reduced, O_2 plasma induced-damage on the porous low-*k* films at the bottom remains unchanged, while that damage on those at the sidewall is mitigated owing to a reduction of the flux of active oxygen species. Therefore, O_2 plasma-induced damage on porous low-*k* films is not increased as the trench structure is miniaturized. Finally, a blanket film can be feasibly used to monitor plasma damage on porous low-*k* films because a plasma process has a detrimental effect on low-*k* films at the bottom of a trench structure.

1. Introduction

Porous low-*k* dielectric materials with a dielectric constant (*k*) below 2.8 in back-end-of-line (BEOL) as inter-metal-dielectric insulator are needed for the complementary metal-oxide-semiconductors technology node from 45 nm and below according to the International Technology Roadmap for Semiconductors (ITRS) [1]. Adopting porous low-*k* dielectric materials brings many advantages, such as the reduction in the resistance-capacitance delay and the power consumption, and the increase of the signal to noise ratio for integrated circuits [2–5]. However, owing to the presence of pores in the film, porous low-*k* dielectric materials have weak mechanical strength and poor electrical performance, leading to more challenges as they are integrated into BEOL interconnects [5,6].

Plasma damage on porous low-*k* dielectric films is one of the critical issues for the integration. During the fabrication of BEOL interconnects, plasma technology is widely used in the deposition, etching, stripping, cleaning, and surface treatment steps because a plasma process provides many advantages, such as fast production, isotropic profile, etc. [7,8]. In these plasma processes, the porous low-*k* dielectric films between the Cu conductors are inevitably exposed to a plasma environment. The generated energetic ions, electrons, highly reactive radicals, and light (from deep vacuum ultraviolet to infrared) in a plasma process physically and chemically react with the low-*k* dielectric films, causing a film modification, and finally increasing the dielectric constant. This phenomenon is called a "plasma damage" [9,10]. More severe plasma damage can occur on porous low-*k* dielectric films because the penetration depth of plasma-generated reactive species increases owing to the presence of pores in a film [11]. Moreover, among the used gases in the plasma process, O_2 gas has reportedly induced the most detrimental effect on porous low-*k* dielectric films due to the high reactivity of oxygen ions and atoms with Si$-$$CH_3$ groups in the low-*k* dielectric film [7,12,13]. O_2-based plasma is typically used in stripping process because of the higher resist removal rate. Regarding the investigation for the plasma damage on the low-*k* dielectric films, most studies used blanket films to irradiate the plasma due to simplicity [14–16]. However, in the actual BEOL interconnects, low-*k* dielectric films at both the sidewall and the bottom of the trench structure are irradiated during a plasma process. Therefore, plasma irradiation on the blanket films can only reflect the plasma damage on the low-*k* dielectric film at the bottom of the trench structure. On the other hand, the evaluation of the plasmas damage on the low-*k* dielectric film at the sidewall of the trench structure is very lacking, due to the relative difficulty and complexity in the fabrication of a real trench structure. Even if it were

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https://doi.org/10.1016/j.tsf.2018.03.049
Received 9 December 2017; Received in revised form 16 March 2018; Accepted 16 March 2018
0040-6090/

Please cite this article as: Cheng, Y.-L., Thin Solid Films (2018), https://doi.org/10.1016/j.tsf.2018.03.049

conducted, the plasmas damage analysis for the sidewall low-*k* dielectric films is relatively difficult, and other integration processing steps may interfere with the result. Thus, research about plasma damage on the low-*k* dielectric film at the sidewall of the trench structure is quite rare [17]. Therefore, a simple and easy method to evaluate the plasma damage on the low-*k* dielectric films at the sidewall of the trench structure is necessary and essential.

In this study, an easy method to produce a simple trench structure was proposed. This method does not require complicated semiconductor processes. The impacts of O_2 plasma on the physical, electrical, and reliability characteristics of the porous low-*k* dielectric films at the sidewall and bottom of the designed trench structure were then compared. Moreover, the effect of the trench width was assessed to understand the scaling impact and the damage mechanism.

2. Experimental details

The studied porous low-*k* dielectric films were deposited on *p*-type (100) silicon substrates by plasma-enhanced chemical vapor deposition using Applied Material Producer® tool. The porous low-*k* films were deposited from diethoxymethylsilane (DEMS) and alpha-terpinene (ATRP) as a matrix and a porogen precursor, respectively. The flow rates of DEMS and ATRP were 850 and 2100 sccm (standard cubic centimeter per minute). The deposition precursors were introduced into the reaction chamber using He as carrier gas. O_2 gas with a flow rate of 200 sccm was also introduced as an oxidant. The deposition temperature, pressure, and power were 300 °C, 1.0×10^4 Pa, and 600 W, respectively. The dielectric constant of the resulting low-*k* film with containing porogen was determined to be 2.85. Then, ultraviolet curing at 300 °C with 200–450 nm wavelength was performed to remove the organic porogen for 300 s. The produced porous low-*k* dielectric film was SiCOH film with the pore size of 1.35 nm and porosity of 15%, which were determined from the isotherm of ethanol adsorption and desorption using ellipsometric porosimetry (Semilab, Mode PS-1100). The thickness and dielectric constant were about 300 nm and 2.56, respectively.

After the deposition of a porous low-*k* dielectric film, the blanket wafer was diced to rectangle-shape sample. The rectangle-shape samples were then constructed to form ⊔ shape, as shown in Fig. 1, in order to simulate the real trench structure. The height of the designed trench structure is 0.9 cm. The width of the designed trench structure can be adjusted ranging from 0.25 cm to 1.0 cm. Then, this designed trench structure was tested in an O_2 plasma environment using a 13.56 MHz inductively-coupled plasma chamber. The bias power applied at the bottom substrate electrode was 0 W. The temperature, pressure, and RF power of O_2 plasma treatment were 25 °C, 2.25×10^{-4} Pa, and 60 W, respectively. The treatment time and O_2 flow rate were fixed at 60 s and 100 sccm. After completing O_2 plasma treatment, the ⊔ structure was disassembled into the planar structures for further analysis.

The thickness of porous low-*k* films before and after O_2 plasma treatment was analyzed on an optical-probe system with an ellipsometer. The water contact angle (WCA) was determined as the average of five measurements (Reme Hardt, Mode 100-00-230). The chemical composition of porous low-*k* films was identified using Fourier transform infrared spectroscopy (FT-IR; Bio-Rad, Model 2200ME) with a resolution of 1 cm^{-1}. An average of 64 spectra in the 400–4000 cm^{-1} range was obtained.

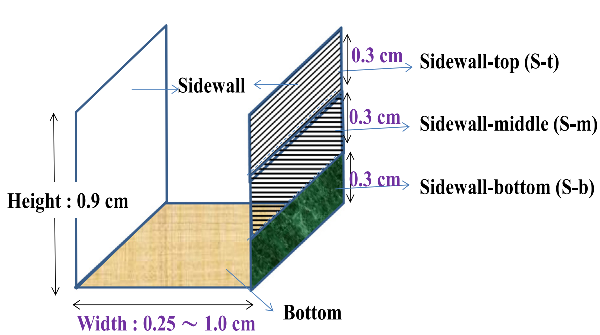

Fig. 1. A designed trench structure used in this study.

The regular pattern of Al metallization with a thickness of 100 nm was deposited onto the porous low-*k* film using a thermal evaporation method through a shadow mask, yielding a metal-insulator-semiconductor (MIS; Al/low-*k*/silicon) capacitor structure for electrical and reliability characterization. The area of Al metal gate in the MIS capacitor structure was $300 \times 300\ \mu m^2$. The dielectric constant (*k*) was determined by capacitance–voltage measurements at 1 MHz using a semiconductor parameter analyzer (HP4280A). Leakage current and time-dependent-dielectric-breakdown (TDDB) were carried out by an electrometer (Keithley, 6517A). The breakdown voltage or time is defined as the voltage or stress time at a sudden rise of at least three decades of the leakage current. All measurements were performed at room temperature (25 °C).

3. Results and discussion

Fig. 2 plots the increase in the dielectric constant of a porous low-*k* dielectric film at the sidewall and bottom of a designed trench structure upon treatment with O_2 plasma for 60 s. The effect of the trench width on the dielectric constant is also shown. O_2 plasma-treated porous low-*k* dielectric films at the sidewall and bottom of the designed trench structure had a higher dielectric constant than the un-treated film ($k = 2.56$), revealing that treatment with O_2 plasma destroys the low-dielectric characteristics of a porous low-*k* film at the sidewall and bottom of a trench structure. Moreover, with respect to porous low-*k* dielectric films in the designed trench structure with various widths, the dielectric films at the bottom exhibited a larger increase in dielectric constant than those at the sidewall, revealing that the damage that was caused by O_2 plasma on the porous low-*k* dielectric films at the bottom of the trench structure was relatively severe. During irradiation in the O_2 plasma, all generated species, including ions, electrons, radicals, and photons, can reach and react with low-*k* dielectric films at the bottom of the trench structure, modifying their structure and increasing their dielectric constant. However, some of the species that are generated by the O_2 plasma cannot reach the sidewall low-*k* dielectric films owing to either shielding or an anisotropic effect. Therefore, O_2 plasma irradiation is expected to induce a relatively weak modification of the porous low-*k* dielectric films. The increase in the magnitude of the dielectric constant of the porous low-*k* dielectric films in the designed trench structure as a result of O_2 plasma treatment decreased as the trench width decreased, indicating that fewer reactive species that were

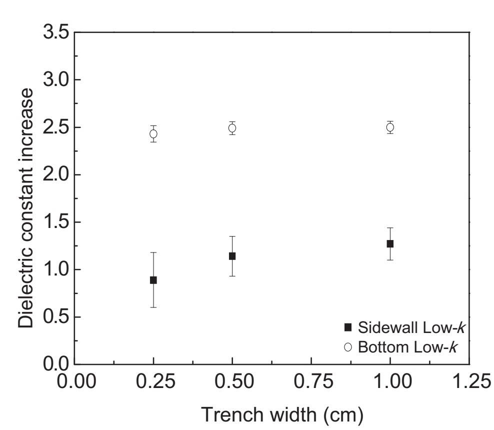

Fig. 2. Change of dielectric constant for porous low-*k* films at the bottom and sidewall of the designed trench structure with different widths under O_2 plasma treatment.