



Effect of high-frequency on etching of SiCOH films in CHF₃ dual-frequency capacitively coupled plasmas

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ABSTRACT

The effect of high-frequency (HF) frequency on etching characteristics of SiCOH films in a CHF₃ dual-frequency capacitively couple plasma driven by 13.56 MHz/2 MHz, 27.12 MHz/2 MHz or 60 MHz/2 MHz sources was investigated in this work. The surface structure of the films after etching and the CHF₃ discharge plasma were characterized. The increase of HF frequency reduced the critical HF power for the etching, suppressed the C:F deposition at the surface of etched films, and improved the etching of SiCOH films. The improvement of etching was attributed to the increase of ions energy and F concentration at high HF frequency.

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1. Introduction

In order to reduce the signal propagation delay, power consumption and cross-link between metal interconnects caused by the device dimension continuous shrinking in ultralarge-scale integrated chips, porous SiCOH low dielectric constant (low- k) and ultralow dielectric constant (ultralow- k , $k < 2$) materials become a promising candidate [1–4]. Recently, the etching of porous SiCOH films has been paid great attention. Due to the existence of pores in SiCOH films, the etching rate of films can increase with reduced film density, resulting in the roughness, the formation of micro-trenches, and the variation in the etched depth, which make the precise profile control of etched patterns uncontrollable [5]. Therefore, the etching of porous SiCOH low- k films is still the dominant challenge in logic technology, and the continual refinement of current capacitively coupled plasma (CCP) source technology is expected to address the problems [6].

The dual-frequency (DF) plasma, in which the plasma density and ions energy can be controlled independently by the high-frequency (HF) and low-frequency (LF) powers respectively, is a powerful tool in the etching of SiCOH low- k films [7,8]. The various DF plasmas, such as 13.56 MHz/1 MHz, 27 MHz/2 MHz and 60 MHz/2 MHz plasmas, have been used to etch the SiCOH films [9–12]. The effect of LF power on etching of SiCOH films was also analyzed [12]. However, how to choose the HF source is not fully understood. Usually, increasing the HF frequency can make the two sources decoupling and leads to the

increase of plasma density [8]. But the simulation indicated that increasing the HF frequency also led to the shift of ions energy to higher energy region [13]. During etching SiCOH films, not only the dissociation of etching gas is controlled by the HF source, but also the surface reactions at the etched films depend on the ions energy on the wafer [14]. Therefore, the effect of HF frequency on SiCOH films etching is more complex, and the better understanding on the effect of HF frequency is needed.

In this work, we investigated the etching characteristics of SiCOH films in the trifluoromethane (CHF₃) DF-CCP driven by the HF frequency of 13.56 MHz, 27.12 MHz or 60 MHz and the LF frequency of 2 MHz simultaneously. The effect of HF frequency on etching rate, bonding configurations of the films and CHF₃ plasma characteristics was analyzed.

2. Experiments

The SiCOH films ($k=2.88$) used in this work were prepared by decamethylcyclopentasiloxane electron cyclotron resonance plasma, which has been described in detail previously [15]. The etching of SiCOH films was carried out in a DF-CCP system [16]. The plasma was produced between two symmetrical plate electrodes. The RF generator (13.56 MHz, 27.12 MHz or 60 MHz) was used as the HF source applied to the top electrode. The HF power was obtained by subtracting the reflect power from the input power. The SiCOH films were placed at the bottom electrode driven by 2 MHz source with the power from 10 W to 40 W. The diameter of two electrodes was 200 mm and the gap between two electrodes was 50 mm. The base pressure of the chamber was approximately 10^{-3} Pa and the working pressure was kept at 50 Pa.

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CHF_3 (99.999%) with the flow rate of 10 sccm was used as the etching gas. The treatment time was kept at 5 min.

The etching rate was calculated from the films thickness (300–900 nm) measured by ET350 profiler with the resolution of 10 nm. The bonding configurations of the SiCOH films after etching were characterized by JASCO 600 Plus Fourier transform infrared (FTIR) spectroscopy in the wavenumber range of 600–4000 cm^{-1} with the resolution of 3 cm^{-1} . The FTIR data was analyzed using the JASCO Spectra Analysis program.

The chemical state of the SiCOH films after etching was identified by X-ray photoelectron spectroscopy (XPS). Photoelectron spectrum was acquired with a Kratos XSAM-800 spectrometer equipped with a hemispherical electron analyzer and an $\text{Al K}\alpha$ irradiation (1486.6 eV) powered at 168 W with the resolution of 0.9 eV. The pressure in the ion-pumped analysis chamber was 6×10^{-7} Pa during data acquisition. The F1s and C1s energy regions were taken in increments of 0.05 eV. The instrument was calibrated by Au 4f_{7/2} binding energy at 84.0 eV. The surface cleaning was applied on the films in the XPS chamber with 3 keV Ar^+ ions ($10 \mu\text{A}/\text{cm}^2$, 5 min). The C 1 s spectra were fitted with Gaussian profile using ORIGIN 6.1 software. The Shirley-type background was subtracted from C 1 s and F 1 s spectra.

The relative radical concentration in the plasma was measured using optical emission spectroscopy (OES) (AvaSpec-2048 fiber optic spectrometer) with 0.5 sccm argon gas (Ar , 750.4 nm) as the actinometry. The optical emission signals in the wavelength range of 200–800 nm with the resolution of 0.05–0.13 nm were collected via a fiber equipped with a CCD detector located at approximately 2–5 mm above the SiCOH film. For the reactive CHF_3 plasma, the electron excitation temperature T_e , which corresponded to the electron energy exciting atoms from the ground to the excited state, was determined by the relative intensity of H_α (656.3 nm) and H_β (486.1 nm) spectral lines according to the following equation [17]:

$$kT_e = (E_2 - E_1) \left[\ln \left(\frac{I_1 \lambda_1 g_2 A_2}{I_2 \lambda_2 g_1 A_1} \right) \right]^{-1} \quad (1)$$

where E_i was the energy of excited state, I_i was the intensity of irradiation, g_i was the statistical weight, λ_i was the wavelength of emission, and A_i was the Einstein coefficient for spontaneous emission. The values for temperature calculating were available from Ref. [18].

3. Results and discussion

The dependence of the etching rate of the SiCOH films on the HF frequency is shown in Fig. 1. A transition from film deposition to film etching is observed. For the different HF frequency, the HF powers needed for the transition can be reduced by increasing HF frequency

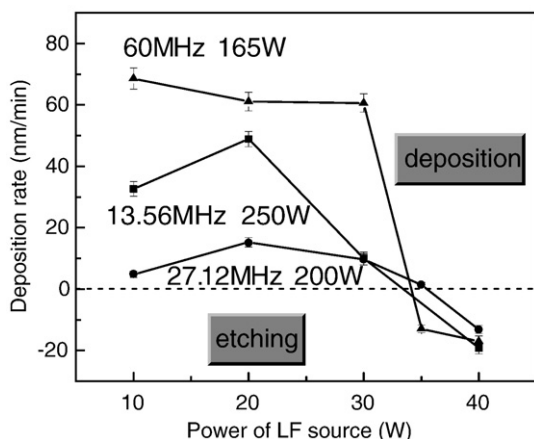


Fig. 1. Etching rate of SiCOH films at different HF frequencies.

while keeping the same LF powers. At the HF frequency of 13.56 MHz, the HF power must reach 250 W, but for the 27.12 MHz and 60 MHz, the HF powers can be reduced to 200 W and 165 W, respectively. If the HF powers lower than the above values are used while the LF powers are in the range of 10–40 W, no film etching can be obtained. Therefore, increasing the HF frequency can reduce the critical HF power needed for SiCOH etching in the CHF_3 DF-CCP.

To understand the effect of HF frequency on film etching, the bonding configurations of the films after etching were analyzed by FTIR, as shown in Fig. 2. For the films etched at the HF frequency of 13.56 MHz and the LF power of 20 W, the absorption peaks mainly come from the Si–O–Si (1064 cm^{-1}), C–F₂ (1175 cm^{-1} and 1215 cm^{-1}), Si–F in SiF_3 (946 cm^{-1}) and Si–O (805 cm^{-1}). No other obvious CF_x absorption peaks are seen. However, the CF absorption peaks at 1030 cm^{-1} , 1070 cm^{-1} , 1100 cm^{-1} and 1050 cm^{-1} may overlap with the Si–O–Si peak. The obvious CF_2 absorption peak in the wavenumber range of 1160 to 1220 cm^{-1} indicates the plentiful C:F deposition after the etching. The existence of Si–F absorption peak in the spectrum indicates that the F is incorporated into the SiCOH film by the reaction between F and Si at the C:F/SiCOH interface. The shift of Si–O–Si absorption peak from 1030 cm^{-1} for the as-deposited film to 1064 cm^{-1} for the film after etching is related to the change of Si–O–Si bond angle due to the F incorporating into SiCOH film. With the LF power increasing to 40 W, the decrease of CF_2 absorption peaks indicates the less C:F deposition. Due to the volatilizing of reaction product from the etched film, no Si–F absorption peak is observed, and the Si–O–Si absorption peak shifts to 1036 cm^{-1} again. Therefore, the transition from film deposition to film etching relates to the less C:F deposition. When increasing the HF frequency to 27.12 MHz (200 W) and 60 MHz (165 W), the CF_2 absorption peaks further reduce, the Si–O–Si absorption peaks still keep at 1036 cm^{-1} , and the Si–CH₃ absorption peaks at 1267 cm^{-1} and 886 cm^{-1} appear. The results mean that the C:F deposition further reduces when increasing the HF frequency to 27.12 MHz and 60 MHz. Hence, increasing the HF frequency can suppress the C:F deposition efficiently, and improve the etching of SiCOH films.

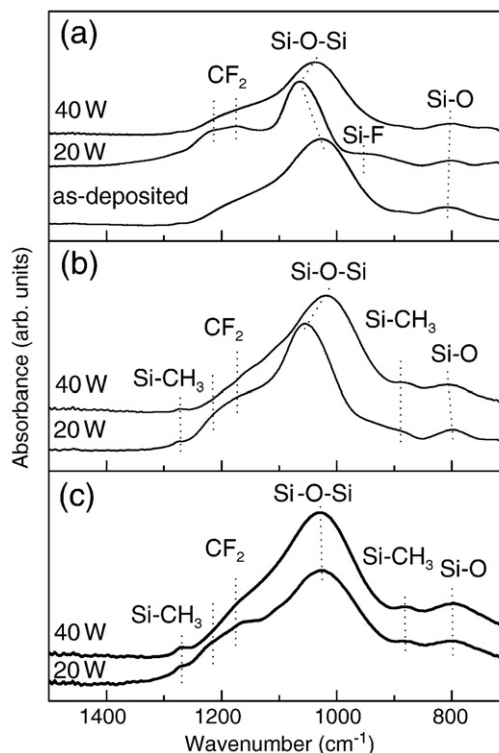


Fig. 2. FTIR spectra of the SiCOH films etched at (a) 13.56 MHz, 250 W, (b) 27.12 MHz, 200 W, and (c) 60 MHz, 165 W.

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