

Chapter 2

On-wafer UV Sensor and Prediction of UV Irradiation Damage

Abstract UV radiation during plasma processing affects the surface of materials. Nevertheless, the interaction of UV photons with surface is not clearly understood because of the difficulty in monitoring photons during plasma processing. For this purpose, we have previously proposed an on-wafer monitoring technique for UV photons. For this study, using the combination of this on-wafer monitoring technique and a neural network, we established a relationship between the data obtained from the on-wafer monitoring technique and UV spectra. Also, we obtained absolute intensities of UV radiation by calibrating arbitrary units of UV intensity with a 126 nm excimer lamp. As a result, UV spectra and their absolute intensities could be predicted with the on-wafer monitoring. Furthermore, we developed a prediction system with the on-wafer monitoring technique to simulate UV-radiation damage in dielectric films during plasma etching. UV-induced damage in SiOC films was predicted in this study. Our prediction results of damage in SiOC films shows that UV spectra and their absolute intensities are the key cause of damage in SiOC films. In addition, UV-radiation damage in SiOC films strongly depends on the geometry of the etching structure. The on-wafer monitoring technique should be useful in understanding the interaction of UV radiation with surface and in optimizing plasma processing by controlling UV radiation.

Keywords On-wafer UV sensor • UV spectrum • Absolute UV intensity • Electron-hole pair • Neural network • Low-k dielectric film

2.1 Introduction

Plasma processes are essential in the fabrication of ultra-large-scale-integrated circuits. There are many activated species in plasma, such as charged particles, radicals, and photons. Etching and deposition processes can be achieved with these activated species. It is important to understand the interaction between plasma and

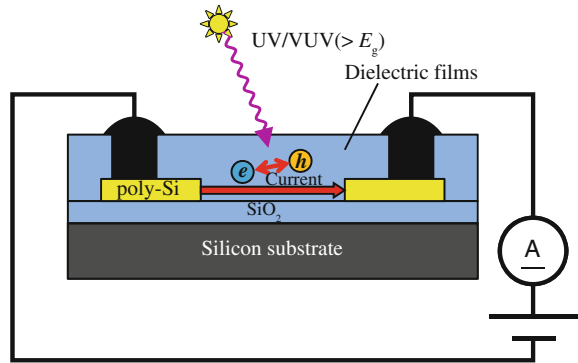
surfaces to precisely control plasma etching processes. The interaction of photons with surfaces is not particularly well understood because of the difficulty of monitoring photons during plasma processing. Several studies have reported the effects of photons on surfaces during plasma processing. High energy photons, such as ultraviolet (UV) and vacuum ultraviolet (VUV) photons, generate electron–hole pairs in SiO_2 films, resulting in various types of process damage, such as shifts in the threshold voltage of metal oxide semiconductor transistors [1] and the formation of crystalline defects [2, 3]. Moreover, since these photons can dissociate chemical bonds in sensitive materials, such as low-k dielectric films, ArF photoresist films, and organic materials, they can modify the surfaces of materials and cause process damage in these materials during plasma processing [4–9]. It is necessary to obtain UV spectra and their absolute intensity from plasma to understand what effects photons have on surfaces during plasma processing and predict surface phenomena caused by UV radiation. VUV spectrographs can be used to monitor UV radiation [10, 11] for this purpose. However, VUV spectrographs involve such large and expensive systems that they are difficult to use with plasma tools on commercial production lines. Moreover, UV spectra obtained from spectrographs do not always correspond to UV-radiation incidents that occur on wafers due to different fields of view. We previously proposed an on-wafer monitoring technique that enabled UV photons to be monitored during plasma processing on wafers [12–15] to overcome this issue with VUV spectrographs. We developed newly designed sensors for the technique of on-wafer monitoring on an 8 in. commercial production line for this study, and we established a UV spectrum prediction system, where a UV spectrum and its absolute intensity could be obtained with on-wafer monitoring sensors. We also developed this system to predict low-k dielectric damage during plasma etching [16].

2.2 Experiment

2.2.1 On-wafer Monitoring Technique

Our newly designed on-wafer UV sensors were used in the technique of on-wafer monitoring. The structure of an on-wafer UV sensor is schematically illustrated in Fig. 2.1. On-wafer UV sensors were fabricated on a commercial production line and two embedded poly-Si electrodes in dielectric films were deposited on an Si wafer. The dielectric films on the poly-Si electrodes were 150 nm thick. When an on-wafer UV sensor is irradiated with UV photons with energy that is at a shorter wavelength than the bandgap energy of the dielectric films, UV photons are absorbed in the dielectric films and generate electron–hole pairs. “Plasma-induced current” flows due to the electrons generated by UV radiation by applying dc voltage between the electrodes. We evaluated the UV radiation from plasma as plasma-induced current. Since the bandgap energy depends on dielectric films, we

Fig. 2.1 Structure of newly designed on-wafer UV sensor. On-wafer UV sensor has two embedded poly-Si electrodes in dielectric films deposited on Si wafer. Thickness of dielectric films on poly-Si electrodes is 150 nm



can detect different UV wavelength ranges by changing dielectric films on a sensor: SiO₂ for UV photons with energies higher than 8.8 eV (wavelengths shorter than 140 nm) and SiN for UV photons with energies higher than 5 eV (wavelengths shorter than 250 nm). In addition, we used SiN/SiO₂ films for UV photons with energies lower than 5 eV (wavelengths shorter than 250 nm). When UV photons are incident to SiN/SiO₂, UV photons with energies higher than 5 eV (wavelengths shorter than 250 nm) can be absorbed in the SiN layer, resulting in the generation of electron-hole pairs. Since the bandgap energy of SiO₂ is higher than that of SiN, electrons cannot flow in the SiO₂ layer. This means that UV photons with energies higher than 5 eV (wavelengths shorter than 250 nm) do not contribute to plasma-induced current. Other UV photons, on the other hand, with energies lower than 5 eV (wavelengths longer than 250 nm) can penetrate through SiN/SiO₂ layers and be absorbed in the interface between SiO₂ and Si because the energy to generate electron-hole pairs at the interface between SiO₂ and Si is 3.1 eV, which corresponds to 400 nm [17]. Hence, the on-wafer UV sensor with SiN/SiO₂ can detect UV photons with wavelengths longer than 250 nm. A wide range of UV wavelengths can be covered with these three different dielectric films.

Figure 2.2 is a schematic of the measurement setup for the technique of on-wafer monitoring with a plasma chamber. Inductively coupled plasma (ICP) (13.56 MHz) was used to generate high-density plasma of more than 10^{11} cm^{-3} . The on-wafer UV sensors were located on a stage in the plasma chamber where the wafer was usually placed and irradiated with plasma. Lead wires were attached to the electrode pads and connected to an ampere meter and a dc voltage source outside the plasma chamber. We applied 20 V to allow plasma-induced currents to flow between the electrodes. Radio frequency (rf) filters were also used to eliminate rf signals from the plasma during measurements. In addition, a VUV spectrograph was installed at the bottom of the chamber through an 80 mm high and 1 mm diameter pinhole to measure the UV spectrum, and photons were detected at a photomultiplier tube. Electrodes were laterally arranged in the newly designed on-wafer UV sensors, which was different from the previously designed on-wafer UV sensors [12–15]. As the previous on-wafer UV sensors measured plasma-

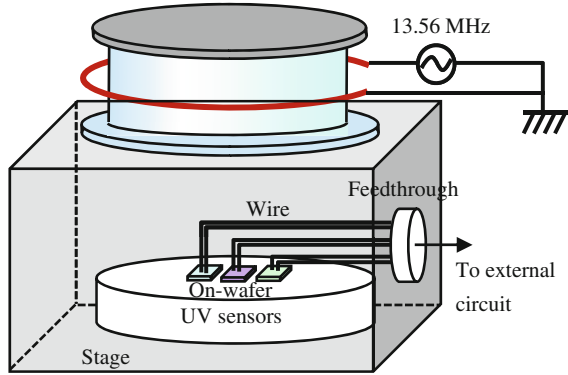


Fig. 2.2 Schematic of measuring setup for on-wafer monitoring technique with plasma chamber. On-wafer UV sensors are located on stage in plasma chamber that wafer is usually placed on and irradiated with plasma

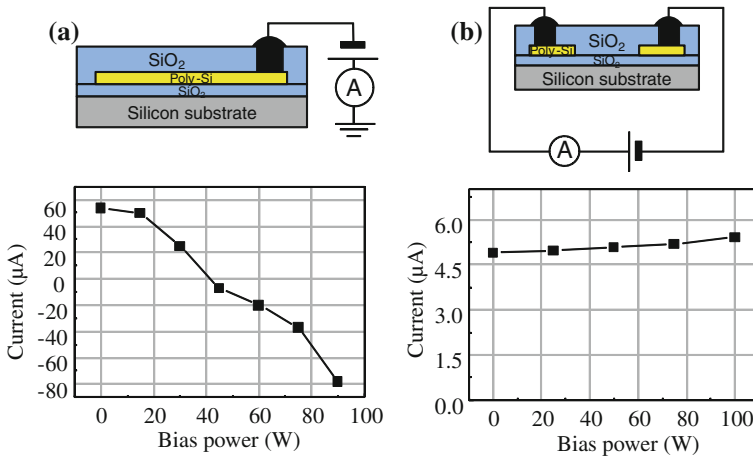


Fig. 2.3 Dependencies of plasma-induced currents on bias power in (a) previously designed on-wafer UV sensor and (b) newly designed on-wafer UV sensor

induced currents between the surface of the sensor and an embedded poly-Si electrode through dielectric films, the currents depended on the bias power applied to the wafer (Fig. 2.3a). However, currents in the newly designed on-wafer UV sensors were measured between electrodes and did not depend on bias power (Fig. 2.3b). Therefore, our newly designed on-wafer UV sensors could be used even for etching processes with bias power.

2.2.2 Predictive System for UV Spectra

Figure 2.4 shows the predictive system for UV spectra. We used a neural technique of network modeling to relate plasma-induced currents to UV spectra to develop the predictive system. The neural network modeling used in this system is given in Fig. 2.5. Since it has been mathematically proven that a three-layered feed-forward neural network can approximate any functions, the network had a three-layered 3-5-35 neuron model. When plasma-induced currents obtained from three different on-wafer UV sensors were input, the total intensities at intervals of 10 nm in wavelength were output. The network was trained on several data sets of plasma-induced currents and UV intensities measured with a VUV spectrograph. Moreover, the absolute intensities of UV spectra were obtained by calibrating arbitrary units of UV intensity with a 126 nm excimer lamp.

2.2.3 Predictive System for UV-Radiation Damage in Dielectric Films

We improved the predictive system using the technique of on-wafer monitoring to simulate UV-radiation damage in dielectric films during plasma etching processing. Figure 2.6 outlines the predictive flow for UV-radiation damage in dielectric films using this technique. The on-wafer monitoring technique could provide a UV spectrum and its absolute intensity. Furthermore, UV photon trajectories directed to dielectric films were modeled by ray tracing, by taking into consideration etching structures, etching rates, and etching times. We assumed that UV photons were radiated from the edges of ion sheaths in these calculations. UV intensities absorbed in dielectric films were calculated with the absorption coefficient of dielectric films based on the UV intensities incident to dielectric films. UV-radiation damage in dielectric films during plasma etching could be modeled by defining the rates at which defects, or damage, were generated. We simulated etching damage in low-k dielectric films induced by UV radiation, based on the damage predictive system using the technique of on-wafer monitoring. Methyl groups are incorporated to reduce the dielectric constant (k) in low-k dielectric films, such as SiOC films. However, as SiOC films are vulnerable to plasma radiation, such as UV photons, radicals, and ions, SiOC films are severely damaged during plasma etching, particularly on the sidewalls of etching structures. This radiation extracts methyl groups from SiOC films, resulting in an increase in their dielectric constant. We clarified the mechanism responsible for damage to SiOC low-k films during plasma etching [5] and found that UV radiation played an important role in the mechanism, viz., UV breaks Si-C bonds in SiOC films and enhances chemical reactions in SiOC films with radicals and/or moisture. It is

Fig. 2.4 Predictive system for UV spectra

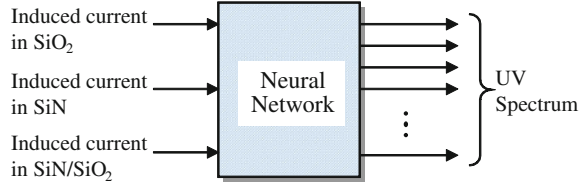
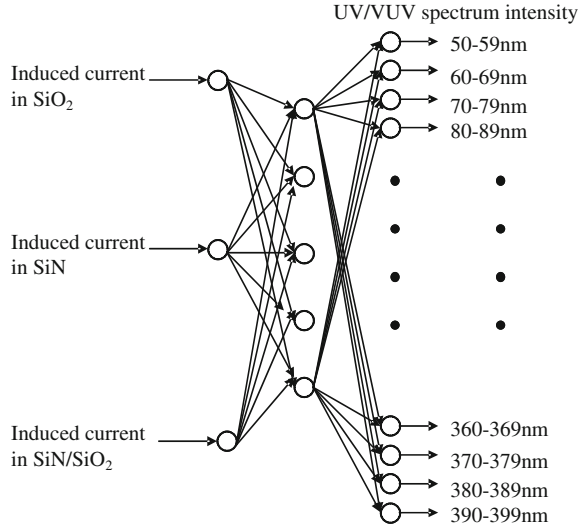
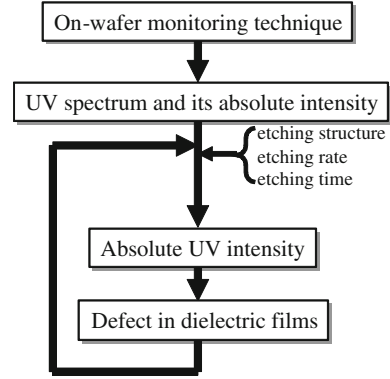


Fig. 2.5 Neural network modeling used in predictive system for UV spectra. Neural network had three-layered 3-5-35 neuron model. When plasma-induced currents obtained from three different on-wafer UV sensors were input, total intensities at intervals of 10 nm in wavelength were output



important to be able to predict damage in SiOC films during plasma etching processes to prevent SiOC films from being damaged and optimize etching conditions. We defined UV-induced damage in SiOC films as the breaking of Si–O and Si–C bonds in the predictions since SiOC films consist of Si–O and Si–C bonds and UV photons have enough energy to break these bonds depending on the energy/wavelength of UV photons. Chemical bonds were assumed to have been broken when UV photons had energies higher (shorter wavelengths) than the dissociation energy of bonds: 8.0 eV (150 nm) in Si–O bonds and 4.5 eV (275 nm) in Si–C bonds. The absorption coefficients of these bonds were supposed to be 10^6 cm^{-1} because the absorption coefficients of SiO₂ and SiC dielectric films are almost the same at the value of 10^6 cm^{-1} [18, 19]. We assumed that Si–O and Si–C bonds were broken by UV photons at the same rate if UV photons were above these bond dissociation energies, according to the absorption coefficients of SiO₂ and SiC dielectric films.

Fig. 2.6 Flow for predicting UV-radiation damage in dielectric films using on-wafer monitoring technique



2.3 Results and Discussion

2.3.1 UV Spectrum and Its Absolute Intensity in Plasma

We collected data sets of UV spectra and plasma-induced currents under varying conditions by changing plasma gases, ICP power, and pressure to train the neural network used to establish the relationship between plasma-induced currents and UV spectra. We measured UV spectra with the VUV spectrograph and obtained arbitrary UV intensities through the measurements. The plasma-induced currents were measured using three types of on-wafer UV sensors. Figure 2.7 plots the neural network predictive results for UV intensities in arbitrary units, compared to the measurements. The plotted data were not used to train the neural network. These results indicate that the neural network could successfully predict UV intensities. The absolute intensity of UV spectra was obtained by calibrating arbitrary units of UV intensity measured with the VUV spectrograph. We used a 126 nm excimer lamp for this calibration, where the power density of UV light was approximately 5 mW/cm^2 at the lamp window. The lamp was installed in a chamber with the VUV spectrograph, as seen in Fig. 2.8. The pressure of the chamber was kept at less than $1 \times 10^{-3} \text{ mTorr}$. Photon flux Γ_λ at wavelength λ is described by:

$$\Gamma_\lambda = k \frac{I_\lambda}{tA}, \quad (2.1)$$

where k is the conversion factor, I_λ is the UV intensity (arbitrary units), and t is the integrated time (0.25 s). Here, A is the irradiated area (0.0079 cm^2). If the conversion factor can be obtained, we can calculate the photon flux of UV light from the UV intensity. The total power density of photons, P , using Eq. (1.1), can be expressed as:

$$P = \int E_\lambda \Gamma_\lambda d\lambda = \int E_\lambda \left(k \frac{I_\lambda}{tA} \right) d\lambda, \quad (2.2)$$

Fig. 2.7 Comparison between UV intensities measured with VUV spectrograph and those predicted with neural network

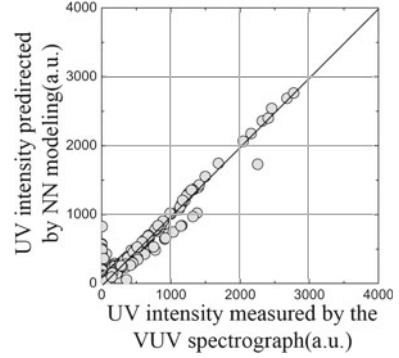
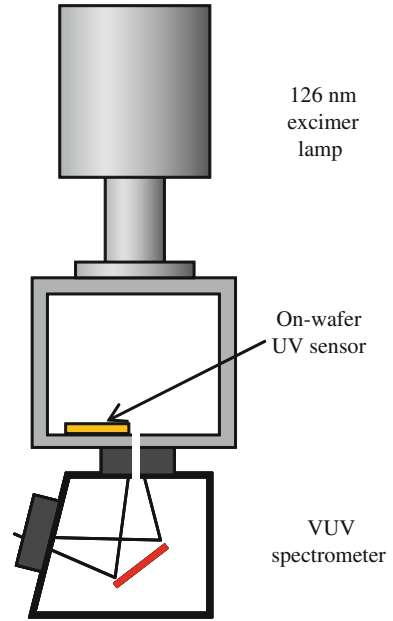


Fig. 2.8 Schematic of experimental setup for 126 nm excimer lamp and VUV spectrograph



where E_λ is the energy of a photon at a wavelength of λ . The power density of UV light, on the other hand, decreased as the distance from the lamp window increased. We measured currents in the sensor, which corresponded to the power density of UV light, as a function of the distance from the lamp window by irradiating an on-wafer UV sensor with UV light from the lamp, as shown in Fig. 2.9. We could acquire the following empirical equation from these results for the dependence of power density of UV light on distance:

$$P = P_0 10^{-\alpha L}, \quad (2.3)$$

Fig. 2.9 Currents in on-wafer UV sensor (SiO_2) under lamp as function of distance from lamp window

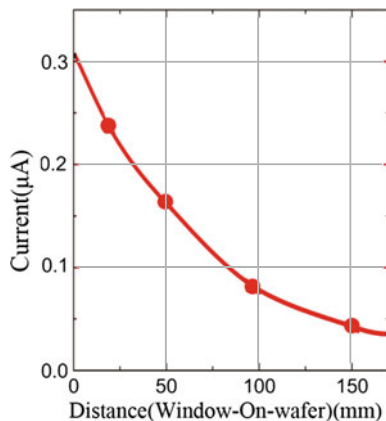
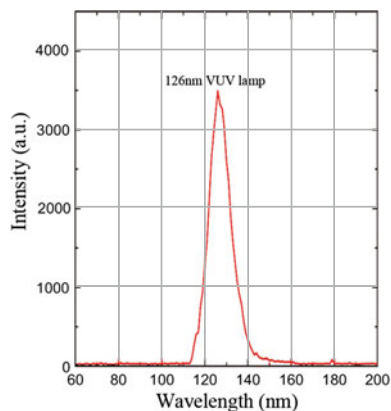


Fig. 2.10 Spectrum of lamp measured with VUV spectrograph



where P_0 is the power density of UV light at the lamp window (5 mW/cm^2), α is a constant (0.006), and L is the distance from the lamp window. The spectrum of the lamp measured with the VUV spectrograph is shown in Fig. 2.10, where a peak can be observed in the wavelength of 126 nm. We obtained $k \sim 2 \times 10^9$ by integrating UV intensities in the spectrum of the lamp and equating Eqs. (2.2) and (2.3) since the detector was located 230 mm from the lamp window. Using this conversion factor enabled us to calculate the absolute intensities of UV spectra.

Figure 2.11 has examples of UV spectra directly measured with the VUV spectrograph (“measurements”) and those obtained using the on-wafer monitoring technique and calibration (“prediction”) in Ar, CF_3I , and C_4F_8 plasmas under conditions of 1000 W of ICP power, 20 SCCM (SCCM denotes cubic centimeter per minute at STP) of mass flow, and 5 mTorr of pressure. The UV spectra with the technique of on-wafer monitoring agreed well with those measured with the VUV spectrograph. In addition, the comparison of absolute intensities of UV photons in this study and those in the previous study provided reasonably good

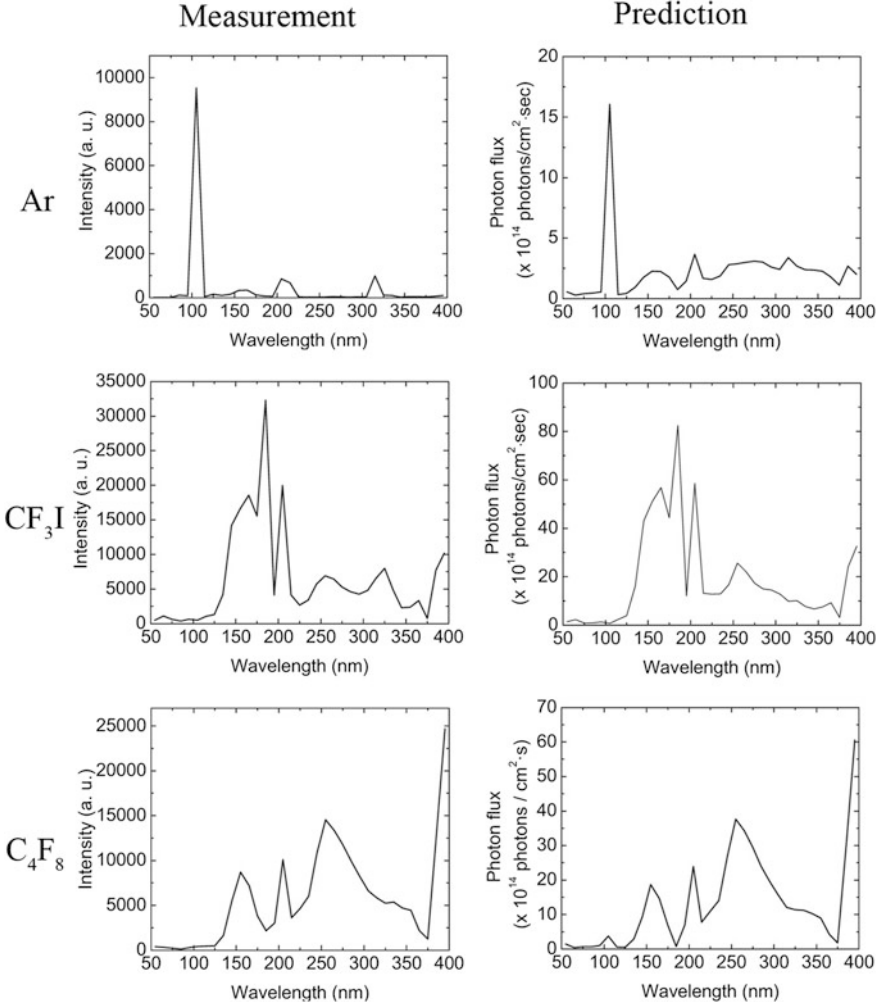
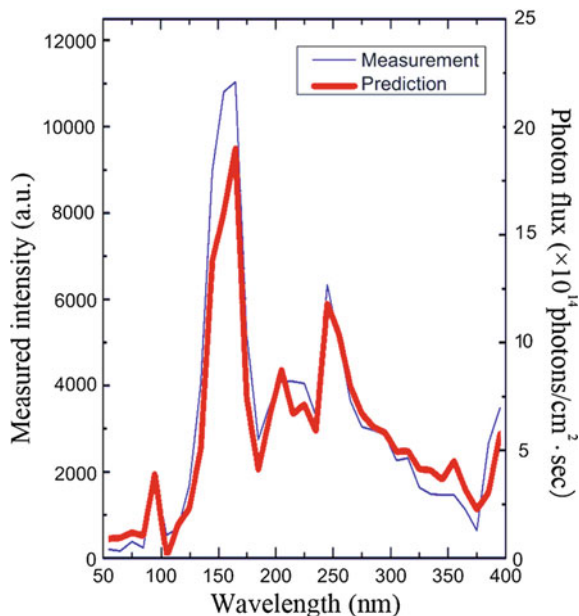


Fig. 2.11 Examples of UV spectra directly measured with VUV spectrograph (measurements) and those obtained with on-wafer monitoring technique (prediction) in Ar, CF₃I, and C₄F₈ plasmas under conditions of ICP power of 1000 W, mass flow of 20 SCCM, and pressure of 5 mTorr

agreement. Woodworth [11] reported that the absolute intensity of UV photons in a wavelength range from 70 to 140 nm in C₄F₈ plasma where $n_e = 3.0 \times 10^{11} \text{ cm}^{-3}$ and $T_e = 4 \text{ eV}$ was $3.0 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$ based on measurements with a VUV spectrograph. However, the absolute intensity of UV photons in the same range was about $1 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$ under similar plasma conditions (C₄F₈ plasma, $n_e \sim 3 \times 10^{11} \text{ cm}^{-3}$, and $T_e \sim 4 \text{ eV}$). This means that the technique of on-wafer monitoring could successfully provide an UV spectrum and its absolute intensity during plasma processing.

Fig. 2.12 UV spectrum and its absolute intensities in CF_4 plasma obtained with on-wafer monitoring technique



2.3.2 UV-Radiation Damage in Low- k Dielectric Films

We used CF_4 plasma to predict damage from radiation. The UV spectrum and its absolute intensities in CF_4 plasma were obtained using the technique of on-wafer monitoring, as seen in Fig. 2.12. The etching structure of SiOC films with hard masks in the trench structure was modeled, as can be shown from Fig. 2.13. We assumed that the etching rate was 60 nm/min, the etching time was 100 s (just etching), and that the hard mask perfectly absorbed UV photons, viz., there were no transmissions or reflections from the hard mask during plasma etching. The results for predicting damage in Si–O and Si–C bonds at etching depths of 25, 50, and 100 nm are given in Fig. 2.14. These results give us several insights into UV-radiation damage in SiOC films during plasma etching. First, no great damage can be observed at the bottom of the trench structure, compared to its sidewalls. This is because the damaged layers at the bottom were removed during plasma etching. Second, the damaged layer in Si–C bonds was much larger than that in Si–O bonds. This means that most of the damage during the etching of SiOC films with CF_4 plasma was not induced in Si–O bonds, but in Si–C bonds because the Si–C bonds were sensitive to a wider range of UV radiation than Si–O bonds. In addition, the UV spectra in the plasmas were the keys to the cause of damage in SiOC films. There is a smaller number of photons in wavelength ranges of less than 150 nm according to the UV spectrum in CF_4 plasma, compared to ranges of less than 275 nm, which can also explain the difference in damage between Si–O and Si–C bonds. Finally, it was apparent that the damage layer increased as

Fig. 2.13 Model of etching structure of SiOC films with hard masks in trench. Etching rate was 60 nm/min, etching time was 100 s (just etch), and hard mask perfectly absorbed UV photons, viz., there were no transmissions or reflections in hard mask during plasma etching

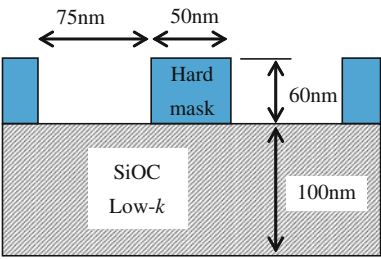
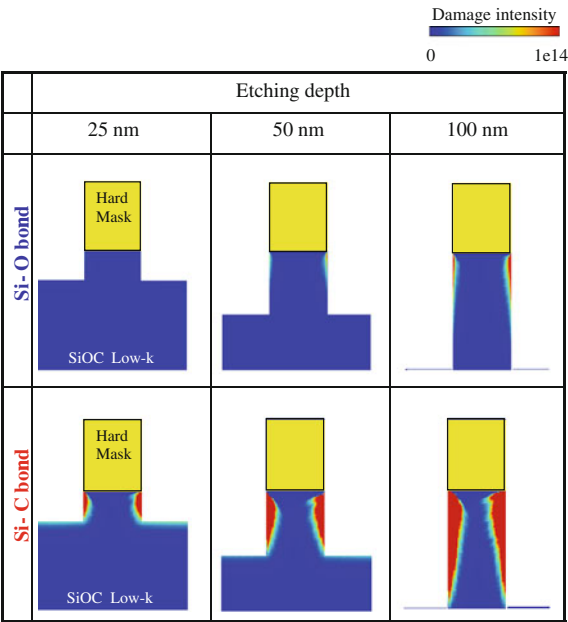


Fig. 2.14 Results from predicting damage in Si–O and Si–C bonds at etching depths of 25, 50, and 100 nm



etching progressed but damage was not found underneath the hard mask. This indicated that UV radiation was shaded by the hard mask. In other words, UV-radiation damage in SiOC films strongly depended on the geometry of the etching structure. The etching damage profile in SiOC films during CF₄ plasma was experimentally investigated by Iba [20]. The etching damage profile was close to the damaged layer in Si–C bonds. This means that UV photons mainly affected the side-wall surface of SiOC films during plasma etching and induced damage by breaking the bonds and enhanced chemical reactions with radicals and/or moisture. If damage was only caused by radicals, it would have been observed even underneath the hard mask because radicals move isotropically and collide with other particles. It was difficult to induce deep damage into sidewalls near the hard mask by ion bombardment because ions were accelerated by rf bias applied to the

wafers. Therefore, the results from prediction clarified that UV spectra and their absolute intensities were important in the formation of damage since damage in SiOC films strongly depends on UV spectra and their absolute intensities.

2.4 Conclusions

UV spectra and their absolute intensities during plasma processing were predicted with our technique of on-wafer monitoring. We established a neural network to relate plasma-induced currents obtained with this on-wafer monitoring and UV intensities measured with a VUV spectrograph. We also calculated the absolute intensities of UV photons by calibrating arbitrary units of UV intensity with a 126 nm excimer lamp. UV spectra could be successfully predicted, and their absolute intensities predicted with our on-wafer monitoring were consistent with those measured with a VUV spectrograph in a previous report. Moreover, we improved the predictive system with on-wafer monitoring to simulate damage in SiOC low-k films during CF₄ plasma etching. The predicted damage profiles of SiOC films were similar to the experimentally obtained damage profiles. We found from these results of prediction that UV radiation damages the Si–C bonds of SiOC films during plasma etching. In addition, our results indicated that UV-radiation damage in SiOC films strongly depended on the geometry of the etching structures. On-wafer monitoring should be useful in understanding the interaction of UV radiation with surfaces and in optimizing plasma processing by controlling the effects of UV radiation.

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