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Prediction of UV/ VUV Irradiation Damage of Interlayer Dielectrics in Plasma Etching Using On-wafer Monitoring Technique

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1. Introduction

Plasma processes are indispensable for the fabrication of ULSI devices. In plasma, there are many activated species, such as charged particles, radicals, and photons. By using these species, etching, film deposition can be achieved. However, UV/VUV photon irradiation from plasma are serious problems because UV/VUV photons can be absorbed in films and generate defects, which may affect surface reaction during plasma processes or device characteristics [1]. UV/VUV radiation can induce the depletion of carbon contents in low-k films, resulting in the increase of the dielectric constant [2]. The structure of ArF photoresist films can be destroyed by UV/VUV radiation, which may cause low-etching selectivity and line-edge roughness (LER) [3]. To decrease the UV/VUV irradiation damage, we have already proposed the on-wafer monitoring, where the intensities of UV/VUV can be precisely observed. In this monitoring technique, the sensor is a wafer- type portable one, which can be easily inserted into the plasma. Our data also revealed that the on-wafer data are strongly related to the device damages. However, the precise analysis of relationship between on-wafer sensor and device damage is needed for the quantitative prediction.

In this paper, we proposed the prediction system of UV/VUV spectrum and UV/VUV damage by using the information of on-wafer sensors. By establishing the relationship between the on-wafer sensors' currents and UV/VUV spectrum by a neural network, the absolute value of UV/VUV spectrum was predicted successfully. In addition, we also predicted the UV irradiation damage of interconnect dielectric by a newly developed damage-prediction system.

2. Experiment

A. On-wafer Monitoring Technique & Experimental

The on-wafer monitoring technique can realize *in-situ* real-time monitoring of effects of UV/VUV photon irradiation just on the wafer [4]. Figure 1(a) showed the schematic illustration of the on-wafer UV sensor. The on-wafer UV sensor has dielectric films with embedded poly-Si electrodes. When the energy of photon is higher than bandgap energy of dielectric films, the photon can be absorbed in the films and generate an electron-hole pair, resulting in the flow of *photon-induced current* between electrodes. The current depends on the type and structure of dielectric films; the current flows in SiO_2, SiN, and SiN/SiO_2 sensors with UV/VUV irradiation with the wavelength of less than 140 nm, less than 250 nm, and more than 250 nm, respectively [4].

We used an inductively coupled plasma (ICP) as plasma source. A one-turn antenna was driven by 13.56 MHz RF, which generated high-density plasma with more than 10^{11} cm^{-3}. The used gases were Ar, CF_3I, and C_4F_8. To measure UV/VUV spectrum from plasma, a VUV spectrograph was installed at the bottom of the chamber through 80-mm-height and 1-mm-diameter pinhole (Fig.1(b)). By using a 126-nm excimer lamp and the on-wafer UV/VUV sensor, we calculated absolute intensity of UV/VUV spectrum obtained by the VUV spectrograph.

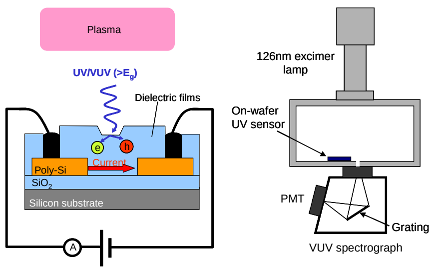

Figure 1 (a) Schematic illustration of the on-wafer UV sensor (b) Schematic illustration of the UV/VUV spectrum observation.

B. UV/VUV Spectrum/ Damage Prediction

To predict UV/VUV spectra based on the plasma induced current data from the on-wafer monitoring technique, we used the neural network (NN) modeling method, because the NN modeling has the capability to learn complex relation ships between groups of related parameters. To relate current of the on-wafer UV sensors to UV/VUV spectrum, we established 3-layered, 3-5-35 neuron model, as shown in Fig. 2(a). It is mathematically proven that 3-layered feed-forward neural network can approximate any functions.

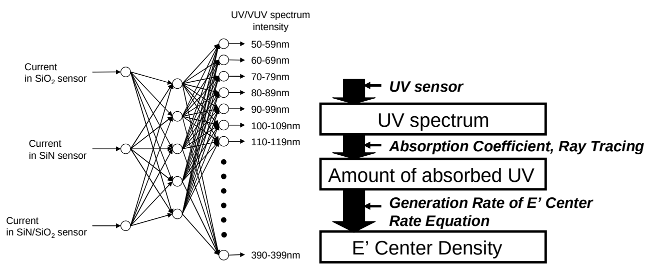

Figure 2. (a) Neural network system for the prediction of UV/VUV spectrum (b) Sequence of calculation of E' Center density.

By using UV/VUV spectrum, device structure, etching rate and processing time, the defect densities in the device were calculated, such as Fig. 2(b). First we calculated the absorbed UV/VUV intensities by the ray tracing technique and the absorption coefficient of the material of device. By using the absorbed UV/VUV intensities and processing time, we can calculate the defect densities by the experiential equations (1) and (2).

$$\frac{\partial n}{\partial t} = \int f \phi d\lambda - \frac{n}{\tau} \qquad (1)$$

n: defect density, ϕ: absorbed UV/VUV intensity, τ: time constant. f is the experiential function on wavelength, such as equation (2).

$$f = 3.21(\lambda - 105.0) + 25.0 \qquad (2)$$

4. Results and Discussion

A. Calculation of Photon Flux

The power density of light from the lamp was known to be 5 mW/cm^2 at the lamp window. The lamp and the VUV spectrograph were installed to a vacuum chamber. Power density of light, P (mW/cm^2), was given by the equation

$$P = \int_\lambda E_\lambda \cdot \Gamma_\lambda d\lambda = \int_\lambda E_\lambda \cdot \left(k \frac{I_\lambda}{tA}\right) d\lambda \qquad (3)$$

where λ: wavelength (nm), E_λ: energy per photon, Γ_λ: photon flux (# of photons/cm^2·sec), I: intensity obtained by VUV spectrograph, t: exposure time (s), A: area of irradiation (cm^2), and k: constant number. On the other hand, we measured the dependence of the current in the SiO_2 sensor under the excimer lamp. We estimated the power density of the light at the pinhole. Hence, from the equation (3),

$k = 4.23 \times 10^{-13}$ (# of photons / spectra intensity). (4)

From the equation (4), we can calculate photon fluxes of UV/VUV photon irradiation from UV/VUV intensities.

B. Prediction of UV/VUV spectrum and damages

We used 9 datasets in the system: 6 for the training of the neutral network modeling and 3 for the prediction of UV/VUV spectrum. Figure 3 showed the predicted profiles of UV/VUV spectrum of Ar, CF_3I, and C_4F_8 plasmas. All spectrums can be successfully predicted. In addition, the UV/VUV intensity can be converted to photon flux. The photon flux obtained from the prediction system using the on-wafer UV/VUV sensor was 10.1 x 10^{14} photons/cm^2·sec, which is comparable to the photon flux (2.9 ~ 30.5 x 10^{14} photons/cm^2·sec) reported in the article [5].

Figure 4 shows the depth profile of E' Center density in SiO_2 after 2-min exposure of plasmas. In He, Ar, O_2 plasma, we can successfully predict the depth profile within the error ratio of 10%. This result shows the validity of this system. Figure 5 shows the E' Center density in SiOC low-k etching. Hole diameter and depth are 22 nm and 44 nm, respectively, corresponding to 22 nm node. We assumed that the C_4F_8 plasma was used and that the etching rate was 60 nm/min. The top area of hole sidewall was significantly damaged about the depth of 20 nm. Such results have never been predicted before. Accordingly, we believe this system is very effective tools for the nano-scaled fabrication.

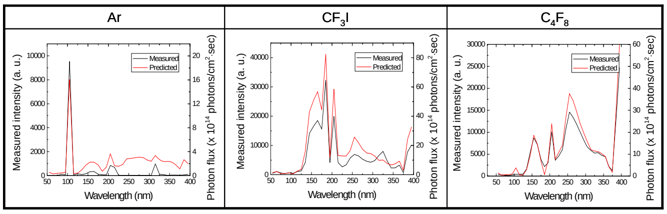

Figure 3. Predicted profiles of UV/VUV spectrum for Ar, CF_3I, and C_4F_8 plasmas.

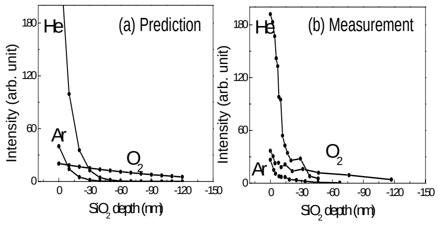

Figure 4. Depth profile of E' Center defect densities (a) predicted results, (b) measured results by ESR.

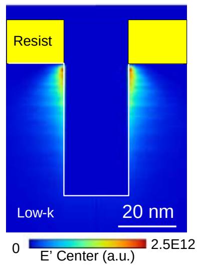

Figure 5 Predicted E' Center density in SiOC low-k etching

5. Conclusion

We showed that the on-wafer monitoring technique can predict UV/VUV spectra and the absolute intensities from plasma. In addition, the defect density in interconnect dielectric can be also predicted by experiential equation by using the information of UV/VUV sensors, device structure etching rate and process time. The on-wafer monitoring technique has many advantages for the investigation of UV/VUV photon irradiation during plasma processes and can contribute to understand the mechanism of damages induced by UV/VUV photon irradiation damages.

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