Control of plasma-surface reactions for next generation semiconductor devices

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Abstract: Dry etching technologies for various devices have been continuously improved for over 30 years as the most advanced application of the low temperature plasmas. In this paper, a brief history of the development of dry etching systems, current issues, and the future technologies for the quantitative control of atomic layer reactions will be discussed.

Keywords: Dry etching, Semiconductor, CMOS

1. Introduction

According to “Moore’s law”, transistor size will be shrunk to below several tenths nanometers. In fabricating high performance ultra-large-scale integrated (ULSI) devices, it is necessary to suppress both the variation of the critical dimension (CD) of the gate electrode and the degradation of the Si substrate (dislocation of Si atoms in the Si-Si network) to within several atomic layers. The length of gate electrodes ($L_g$) depends on the mask profile, including line width roughness (LWR), etch rate uniformity within a wafer and/or within a lot, and the pattern (space) width. The damage to the Si substrate occurs both during gate etching and the etching of sidewall dielectric materials (see Fig. 1).

![Fig. 1 Si recess](image)

The “Si-recess” is a problem caused during etching to fabricate gate electrodes. Although the gate oxide remains when a highly selective etching process is used, some damage occurs under the gate oxide and the damaged Si is recessed during the post-wet treatment, as shown in Fig. 1. The change in profile of source/drain region (near the gate electrode) can be origin of fluctuations in transistor properties. Furthermore, when we apply the same plasma process for gate etching, the depth of the “Si-recess” is not changed although the transistor size will be smaller in the next generation devices and beyond. Consequently, this damage will have more serious impact on transistor properties in the near future. In this report, we clarify the mechanism of formation of the “Si-recess”.

2. Experiment

A dual frequency (60/13MHz) capacitively coupled plasma (CCP) system was used to study Si-recess. The gas pressure was 60mTorr, the ion energy was controlled using substrate bias power, and $V_{pp}$ was varied from 50 to 400 V. We estimated the ion energy distribution function (IEDF) using a Monte Carlo simulation. Penetration depths of ions were estimated using a molecular dynamics simulation. A gate SiO$_2$ layer (1.4 – 300 nm) was formed on the Si substrate and exposed to HBr/O$_2$ and O$_2$ plasma. The damage (degradation of Si-Si network) occurred below the gate SiO$_2$. This damage was analyzed by spectroscopic ellipsometry (SE), high-resolution Rutherford backscattering spectroscopy (HRBS), and transmission electron microscopy (TEM).
3. Results

3.1 Degradation of Si substrate

In a sample with a thin gate oxide (\( T_{ox} = 1.4 \) nm), we observed thick damage after HBr/O\(_2\) plasma exposure. Figure 2 shows the damage thickness (\( T_d \)) under the gate oxide as a function of HBr/O\(_2\) plasma exposure time. As clear in the figure, \( T_d \) gradually increased to about 10 nm at 600 s. However, with O\(_2\) plasma, \( T_d \) did not depend on time and was less than 3 nm. The use of HBr plasma results in thicker and more significant damage.

3.2 Surface analysis

Figure 2 shows the TEM images and depth profiles of HRBS spectra for the Si substrates exposed to HBr/O\(_2\) plasma (\( V_{pp} = 400 \) eV, 600s). Oxygen is diffused deeper than 10 nm along with the dislocated Si generated by the hydrogen penetration.

4. Discussions

4.1 Model for damage formation

The results indicate that the Si substrate (under the gate oxide film) was affected by both: (i) degradation of the Si-Si network by H ions (from HBr), and (ii) diffusion of O radical supplied to the degraded layer. A model of this is illustrated in Fig. 4. The \( T_d \) is assumed to depend on the O diffusion time and to be limited by the H ion penetration depth.

4.2 Calculation of H penetration depth

To quantitatively predict the ion penetration through the gate oxide and the Si degradation, we developed a series of new potential functions for molecular dynamics (MD) simulation for Si, O, C, F, and H systems. Based on the Stillinger-Weber potential [7,8], we prepared three-dimensional potential functions and adjusted them to the first-principal results using Gaussian98. We fabricated a large (2 x 2 x 20 nm) sample structure of a Si substrate topped by a SiO\(_2\) layer (1.4 nm).

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**Fig. 2** Damage thickness as a function of etch time

**Fig. 3** HRBS and TEM results

**Fig. 4** Model for ion assisted diffusion of O radicals

**Fig. 5** MD calculation of H penetration
Hydrogen atoms with energies of 10-300 eV were dosed onto the substrate (Fig. 5). As expected, H penetrated deeply into the Si layer (more than 10 nm), and part of the Si-Si bond degraded.

4.2 Analysis using multi-beam injection system

To confirm the damage formation model, the author and his collaborators used a multi-beam injection system [9]. The multi-beam system consists of three parts, i.e., a mass analyzed ion beam injector, a set of two independently controllable neutral radical/molecular beam injectors, and a reaction chamber in which a sample substrate can be placed (Fig.6). In this system, a monochromatic and mono-energetic ion beam as well as independently controlled radical/molecular beams can be simultaneously injected into a given substrate surface. The ion and radical sources are differentially pumped and therefore the chamber can be maintained at ultra-high vacuum. Using this system, Si surfaces were irradiated by H\(^+\) or Ar\(^+\) ion beam at 500eV each as well as atomic oxygen (O) radical beams. [10, 11]

i) Si-dislocation formed by H ion beam

Figure 7 shows the Si dislocation formed by H\(^+\) injunctons under energy of 500eV. Dislocation was increased by increasing dosage of H\(^+\) ion and the depth of dislocation depended on ion energy.

ii) Ion assisted diffusion of O radical

Next we simultaneously injected O radical with Ar\(^+\) and H\(^+\) ion beam as shown in Fig.8. It has been found that oxygen (O) diffusion is enhanced in the alteration layer due to amorphization of Si by H\(^+\) beam.

Our multi-beam injection experiments corroborates the hypothesis that the Si recess during HBr/O\(_2\) plasma etching processes is caused by H\(^+\) ion injections from HBr plasmas and O radical diffusion.
4.3 Suppression of “Si recess”

An ion energy distribution function (IEDF) in the CCP system was calculated using Monte Carlo simulation (Fig. 9a). Through MD simulation, we found that it was necessary to maintain the ion energy at a level below 50 eV in order to suppress the O penetration through the 1.4-nm gate oxide. By controlling the high energy peak of IEDF below this threshold energy level, we were able to successfully suppress the formation of the Si recess (Fig. 9b). [7]

Thus, it is necessary to clarify the penetration depth and to control the ion energy distribution quantitatively to ensure stable device fabrication in mass production.

5. Conclusions

The mechanism of the Si recess that forms during gate poly Si etching was studied. Hydrogen in HBr plasma penetrates through the thin gate oxide film and induces deep degradation (>10 nm @ 400 eV) in the Si substrate. Simultaneously injected oxygen is diffused to the damaged layer caused by H+ ions, resulting in thick oxidation of the layer. By lowering the high energy peak of IEDF the Si recess was successfully minimized.

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References