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Estimation of defect generation probability in thin Si surface damaged layer during plasma processing

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Abstract

The structural change and defect generation in Si by plasma exposures are investigated by spectroscopic ellipsometry (SE) and photoreflectance spectroscopy (PR). For an Ar-DC plasma exposure with 300 V bias, the SE with an optimized model identifies 1 nm-thick interfacial layer (IL) between the surface layer and the substrate. The PR indicates the mechanical strain change by approximately 0.1%. The PR was applied to an estimation of plasma-induced carrier trap site density on the basis of a model correlating surface potential to the density. Combined with plasma diagnostics, the defect generation probability was estimated for the present condition.

Keywords: Plasma; Silicon; Defect; Ellipsometry; Photoreflectance; Strain

1. Introduction

Plasma processing is widely used in present-day microelectronic industries to meet the requirements of fabricating finer patterns, *i.e.*, the scaling law [1]. Not only Si-based ULSI (Ultra Large Scaled Integrated circuit) but also Micro-Electro-Mechanical Systems (MEMS) are fabricated through many plasma processing steps. As the critical dimension of the feature size in devices has shrunk and new materials have been introduced, several issues concerning plasma processing, *e.g.*, plasma-induced damage (PID) have been pointed out [2–5]. The plasma-induced damage is classified in accordance with the mechanisms [6] as "charging damage" [2,3], "ion-bombardment damage" [4], and "radiation damage" [5]. During the spacer and contact etch processes, the exposure of Si surface to plasma results in lattice damage and contamination problem due to the energetic ion bombardment and penetration of the species involved in the processes. This ion-bombardment damage degrades device performance [7,8], and is one of critical issues in scaled devices with shallower junctions in the contact and source/drain (S/D) extension regions. With regard to the evaluation methods, both the electrical and structural analyses have been conducted so far. In the structural analysis, in addition to spectroscopic ellipsometry used in production lines, reflected high-energy diffraction [5,9], X-ray photoelectron spectroscopy [10], and photoreflectance spectroscopy [11–13] have been employed. In the electrical measurements, the current–voltage measurement with Schottky-contact test structures [7,9,11], sheet resistance measurement [8] and deep-level transient spectroscopy [14] have been performed to investigate the defects in devices. However, compared to extensive studies of the charging damage [3], the defect generation processes have not been investigated so far in terms of a quantitative parameter such as carrier trap site density closely related to the device performances. In order to understand the interaction mechanisms between plasma and devices, a quantitative characterization technique of damaged layers is strongly required.

In this paper, an evaluation technique for plasma-induced carrier trap site density in Si damaged layer will be proposed and the mechanisms will be discussed in terms of defect generation probability determined by optical techniques and plasma diagnostics. Two optical analyses (photoreflectance (PR) and spectroscopic ellipsometry (SE)) are conducted to identify the damaged layer thickness, the mechanical strain change and the carrier trap site density.

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2. Experimental details

2.1. Sample preparation and plasma treatments

After pre-cleaning of the surface, the n-type (100) Si wafers (0.02 Ω cm) were mounted on the stage and exposed to DC plasma sources. Ar was used under the pressure of 2.0×10^{-1} Torr for various process times and dc voltages. The sample without exposure was to be the control. The Langmuir probe measurement determined the electron temperatures and densities as ~3.0 eV and ~10^9 cm^{-3}, respectively.

2.2. Defect characterization techniques

The spectroscopic ellipsometry (SE) and photoreflectance spectroscopy (PR) were conducted to identify the damaged layer thickness and the carrier trap site density. For the analysis of SE spectra, a four-layer (ambient/layer-1/layer-2/substrate) model is assumed. The surface layer (SL) (layer-1) is thin SiO_2. The thickness (d_1) is calculated. The interfacial layer (IL) between SL and Si substrate (layer-2) is introduced as a composite of SiO_2 and poly-Si with the Bruggeman effective medium approximation (EMA) with the thickness (d_2) and volume fraction ($f_{p\text{-}Si}$) being used as fitting parameters. With regard to the optical model for SE analysis, we have found that the present four-layer model can be applied to various plasma-exposed samples, compared to other models with the dielectric functions of SL and/or IL being used as fitting parameters [15].

The other optical analysis conducted is photoreflectance spectroscopy (PR) [16]. In the present PR system, the surface field was modulated by the light from Ar^+ ion laser (514.5 nm) chopped with frequency of 500 Hz. A Xe discharge lamp was used as a probe light source. Two parameters related to the Si surface structures will be determined, *i.e.*, the mechanical strain change and the carrier trap site density as below. The spectral line shape of the reflectance change $\Delta R/R$ is expressed on the basis of the third-derivative theory in the low field limit [16] by the following equation:

$$\frac{\Delta R}{R} = \Re\left[Ce^{i\theta}\left(E - E_g + i\Gamma\right)^{-n}\right], \tag{1}$$

where C, θ and E are amplitude, phase factor and photon energy in the unit of eV, respectively, and the exponent n depends on the dimensionality of the critical points. E_g and Γ are the transition energy at the critical point and the broadening parameter, respectively. The feature of PR line shape near 3.4 eV observed for Si corresponds to the interband transitions associated with the L-point ($n=3$) and/or the Γ-point ($n=5/2$) [17–19]. Since the differences are focused as a measure for changes in surface structures, we fit the experimentally observed spectra by the Γ-point transitions with E_g, Γ and C being determined. (We have confirmed that the same trend was observed concerning E_g and Γ in the case of L-point transition [15].) From E_g, the mechanical strain change is estimated. Moreover, in order to quantify the plasma-induced carrier trap site density, we focus on the characteristic mechanism that $\Delta R/R$ is related to Si surface potential [20–22], as expressed by,

$$C = A_1 \ln\left[A_2 I_p \exp\left(\frac{eV_s}{kT}\right) + 1\right] = A_1 \ln\left[P_2 I_p + 1\right], \tag{2}$$

where I_p, V_s, k and T are irradiating laser power (W), surface potential (V), Boltzmann constant and temperature (K), respectively. A_1 and A_2 (P_2) are material- and structural-dependent parameters. We modify and apply this model to evaluate the plasma-induced carrier trap site per unit area N_{dam} (cm^{-2}). As mentioned in Appendix A, by assuming that the trapped charges induce the change in V_s (ΔV_s) (determined from the least square fit of C versus I_p and the ratio of V_s in control to that in plasma-exposed samples), N_{dam} can be calculated by solving Poisson's equation. Note that N_{dam} is found to be proportional to ΔV_s. Based on the present method, N_{dam} is determined without knowledge of the surface potential [13] in the control in advance.

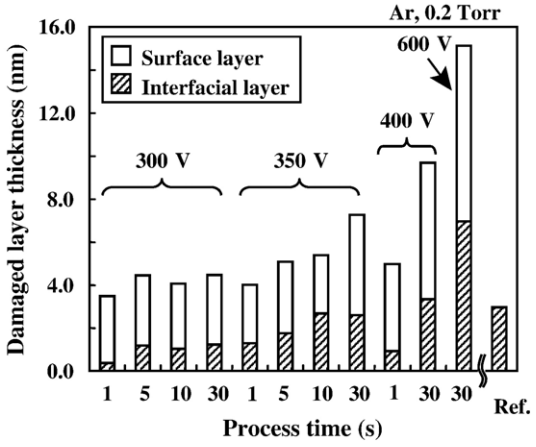

Fig. 1. The thicknesses of the surface and interfacial layers determined from the spectroscopic ellipsometry analysis.

Table 1
Examples for extracted parameters obtained from the SE spectra and the PR analysis for the samples treated by Ar plasmas

Process time (s)	d_1 (nm)	d_2(nm)/$f_{p\text{-}Si}$	ΔV_s (V)	N_{dam}(10^{12} cm^{-2})
1	3.12	0.37/0.76	(−0.001)	(0.34)
5	3.27	1.18/0.70	−0.014	4.3
10	3.03	1.04/0.79	−0.016	5.2
30	3.24	1.22/0.86	−0.026	8.4
Control	2.10	(0.23/0.92)	–	–

3. Results and discussion

Table 1 shows examples of SE results with the four-layer model for the case of 300 V bias. Since the SL and IL correspond to the reaction layer (the damaged layer), the increase in thicknesses with the increase in bias voltage implies more severe damage. Fig. 1 summarizes the results for various samples. The thicknesses for the layers (SL+IL) obtained in this