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Quantitative Characterization of Plasma-Induced Defect Generation Process in Exposed Thin Si Surface Layers

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1. Introduction

Plasma processing has been widely used in present-day microelectronic industries for fabricating finer patterns [1]. In accordance with the scaling law, several issues concerning the plasma processing (e.g., plasma-induced damage (PID)) have been pointed out. Physical damage, one of the PID mechanisms [2], is commonly associated with the damage induced by high-energy ion bombardment and considered to be one of crucial issues from the viewpoints of the physical thickness [2]. One should note the important roles PID plays on degrading the device performances and material qualities. However, there are few reports which "quantitatively" correlate the plasma-induced defects in devices with plasma parameters, requisite for understanding the mechanism. In this paper, the plasma-induced defect site in Si surface layer will be quantitatively analyzed in details by new methods proposed, and the mechanisms of physical damage will be discussed. Defect generation probability, as well as the thickness, key parameters for the plasma process and device designs, will be provided.

2. Experimental

After pre-cleaning of the surface, n-type (100) Si wafers (0.02Ωcm) were mounted on the stage and exposed to DC and ECR (Electron Cyclotron Resonance) plasma sources. Ar-based gas mixtures were utilized for the purpose of eliminating chemical reactions with silicon. The sample without the exposure was to be the control. The operating pressures were 2.0×10^{-1} and 1.0×10^{-2} Torr for DC and ECR (13.56 MHz RF bias with 200 W) plasmas, respectively. In order to determine the plasma parameters, the Langmuir probe and bias voltage measurements were carried out. Two optical analyses, spectroscopic ellipsometry (SE) and photoreflectance (PR), were conducted to identify the damaged layer thickness and the defect density. In the analysis of SE spectra, we adopt a four-layer (air/layer-1/layer-2/Si substrate) model, where the interfacial layer-2 is assumed as a composite of SiO_2 and poly-Si. In the PR analysis, the surface field was modulated by the Ar^+ ion laser. The spectral line shape of the ratio ΔR/R is analyzed on the basis of the third derivative theory [3], i.e.,

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

where C, θ and E are amplitude, phase factor and photon energy, 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 has to be analyzed carefully in terms of the interband transitions, associated with the L-point (n=3) and the Γ-point (n=5/2). Since the differences are focused as the measures for changes in the surface structure, we fit the experimentally observed spectra by Γ-point transition in this study. In order to quantify the plasma-induced defect density, we also focus on the characteristic mechanism that $\Delta R/R$ is related to Si surface potential [4], as expressed by:

$$C = A_1 \ln\left[A_2 I_p \exp\left(V_s / kT\right) + 1\right] \qquad (2)$$

where I_p, V_s, k and T are laser power, surface potential, Boltzmann constant and temperature, respectively. A_1 and A_2 are material and structural dependent parameters. Here we modify and apply this model to evaluate the plasma-induced defect site per unit area (N_{dam}). By assuming that the charges trapped into N_{dam} 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 ($V_s^{ref.}$) to that in plasma exposed samples ($V_s^{dam.}$), N_{dam} can be calculated by solving Poisson equation. Figure 1 illustrates the basic concept of the model estimating defect site generated by plasma processing.

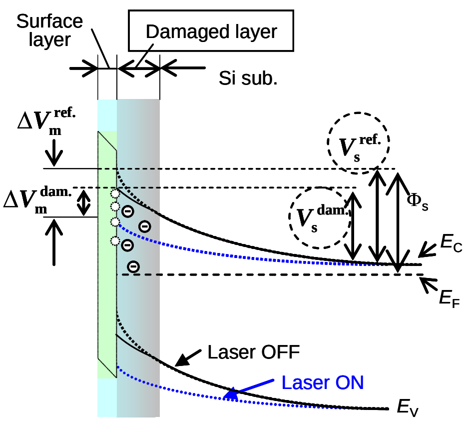


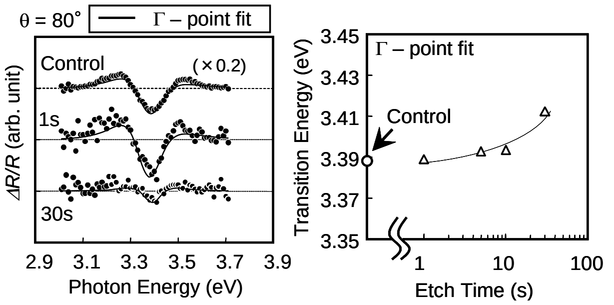
Fig.1 Change in the surface potential in Si surface damaged region during the PR measurements. ΔV_m is the modulated potential.

3. Results and Discussion

Table I shows examples of SE results for DC and ECR plasma cases. The layer-2 is identified to be a plasma-induced damaged layer. Figures 2 (a) and 2 (b) show examples of PR spectra and calculated transition energy at Γ-point for DC plasma, respectively. Similar trends are also found (not shown) for the ECR plasma case and the L-point transition. As the damage becomes more severe, a blue shift from the control is observed. One of the mechanisms for this energy shift is considered to originate from a stress relaxation in the interfacial layer-2 in Table I. (Note that the control suffers from the tensile strain in Si surface region induced by the native oxide layer.) Based on the hydrostatic strain model [5], the change in the strain developing in the interfacial layer is estimated as approximately ~ 0.1 % between the control and exposed (30 s) samples.

Table I. Extracted parameters obtained from the SE spectra. $f_{p\text{-}Si}$ is the fraction of poly-Si in the layer-2.

	Process Time (s)	Layer-1 (nm)	Layer-2 (nm) / $f_{p\text{-}Si}$
DC	1	3.12	0.37 / 0.76
	5	3.27	1.18 / 0.70
	10	3.03	1.04 / 0.79
	30	3.24	1.22 / 0.86
ECR	30	5.17	0.45 / 0.94
Control	-	2.18	-



(a) (b)

Fig. 2 (a)Typical examples for PR spectra of plasma treated samples and (b) calculated transition energy E_g in eq.(1). Angle of incident probe beam is 80º. The solid line in (b) is the guideline for reader's eye.

Figure 3 shows the amplitude C as a function of I_p. Table II lists the change in V_s and the N_{dam} for various cases on the basis of eq.(2). The decrease in the surface potential (ΔV_s) is observed for all exposed samples. This decrease is considered to be due to the presence of acceptor-like charge trap sites with significant density for devices performance.

By assuming the Bohm sheath criterion [6] with the electron temperature (T_e) and density (n_p) being determined from plasma diagnostics, the ion fluxes from plasmas ($F \sim 0.61 n_p (T_e/M)^{1/2}$, where M is mass of ion.) are calculated as 1.7×10^{13} and 6.3×10^{15} ($\mathrm{cm^{-2}s^{-1}}$) for DC and ECR plasmas, respectively. Thus we finally find that the defect generation probability ($\gamma_{dam}(E_{ion})$ = the number of generated defect site per unit area and per an impinging ion with the energy of E_{ion} from plasma) is calculated as approximately in the range from $\sim10^{-3}\ \mathrm{s^{-1}}$ (DC) to $\sim10^{-5}\ \mathrm{s^{-1}}$ (ECR), from $\gamma_{dam}(E_{ion}) = N_{dam}/F/\tau$, where τ is process time. The difference in γ_{dam} is attributed to that in the energy of ions accelerated in the sheath, primarily to that in the measured bias voltage (V_{dc}= -50 V for ECR and -300 V for DC), although the ion energy distribution function [6] has to be taken into consideration for further discussion. This ion energy effect is also confirmed from the difference in Layer-2 thickness in Table I, as well as from the etching simulation (not shown).

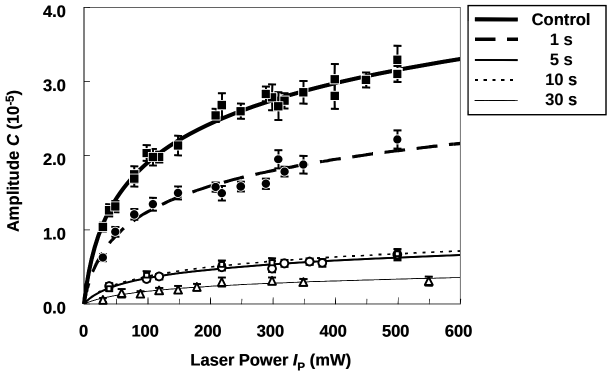


Fig. 3 Calculated amplitude as a function of laser power for various plasma treatments. (Note that the linearity of laser output power versus irradiating energy density has been confirmed.)

Table II. The change in V_s and the number of generated defect site per unit area (N_{dam}). The defect density within the damaged layer (n_{dam}) by SE analysis is also shown for comparison.

	Process Time (s)	ΔV_s (V)	N_{dam} ($10^{12}\ \mathrm{cm^{-2}}$)	n_{dam} ($10^{18}\ \mathrm{cm^{-3}}$)
DC	1	-0.0011	0.34	0.93
	5	-0.0135	4.3	3.7
	10	-0.0162	5.2	5.0
	30	-0.0263	8.4	6.9
ECR	30	-0.0658	21	47

4. Conclusions

The plasma-induced defect site in Si layer was quantitatively studied by the new methods. The interfacial layers with the relaxed mechanical strain (~0.1 %) and charge trap sites which affect device performances ($\sim10^{12}\ \mathrm{cm^{-2}}$) were identified. The obtained defect generation probability (10^{-3}~$10^{-5}\ \mathrm{s^{-1}}$) proposes quantitative implications of PID and a key guideline for future device and plasma designs.

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