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A Framework for Sensitive Assessment of Plasma Process-Induced Damage in Si Substrates

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Abstract

Extremely low defect density is the first requisite for realizing emerging electronic devices such as image sensors. Defect generation during plasma processing is a critical issue and various characterization methods have been proposed so far. This paper provides a framework with respect to highly sensitive defect assessment which can be implemented in plasma and device designs. Various optical and electrical analyses were conducted focusing on the polarity of defects created in Si substrates. The assigned features were found to depend on plasma gas chemistries, suggesting that one should employ an optimized methodology to assess low-density defects.

1. Introduction

In the fabrication of high-performance electronic devices, suppressing unexpected impurities and defects is a critical concern. In particular, defects in a damaged region after plasma processes—plasma process-induced damage (PID)—have attracted much interests. The created defects have unique profiles with respect to the spatial and energy distributions, leading to unpredictable degradation of the performance and reliability of devices [1]. Various characterization techniques have been proposed to quantify the PID density [1]. Recently, a preliminary study on assigning the energy profile of created defects was reported [2]. Not only the density of defects but also the polarity is fundamental and key to designing future high-performance devices [3], in particular, which require extremely low defect density (e.g. image sensor) [4,5]. However, there have been few reports to provide a universal and versatile methodology for PID assessments. In this study, we discussed the sensitivities of optical and electrical characterization methodologies for assigning the polarity of created defects in Si substrates. It was experimentally clarified that the polarity of defects (n- or p-type-like) depends on plasma gas chemistries. Finally, on the basis of present findings, we propose a sensitive defect assessment framework consisting of simple in-line monitoring and device characterization techniques.

2. Experimental

N- and p-type Si substrates with ~0.02 Ω·cm were exposed to inductively coupled plasmas. The working gases were Ar or SF_6 at 2.7 Pa. The process duration was 30 s. The peak-to-peak value of substrate bias voltage V_{pp} which determines the incident ion energy was controlled at 350 and 600 V for Ar and SF_6, respectively. Note that an unexposed sample is denoted as Ref. Typical defect structures on the surface damaged region are shown in Fig. 1(a). The density-of-state (DOS) in the Si bandgap ("defect state") plays a role as carrier trapping and detrapping sites. Various techniques were employed to characterize these defects as shown in Fig. 1(b). Spectroscopic ellipsometry (SE) was used to analyze the change in the optical constants of a damaged layer. Photoreflectance spectroscopy (PRS), a class of modulation spectroscopy, was used to analyze the surface potential change due to the presence of defects in the vicinity of surface (~10 nm). The surface field is modulated by a laser beam chopped at 500 kHz and the resulting change in the dielectric constant is detected as that in reflectance $\Delta R/R$. For the electrical analyses, current–voltage (I—V) and capacitance–voltage (C—V) measurements were conducted using a mercury probing system to analyze the electrical characteristics of the damaged region. For the C—V measurements, the modulation frequency f_{mod} was varied from 10 to 400 kHz.

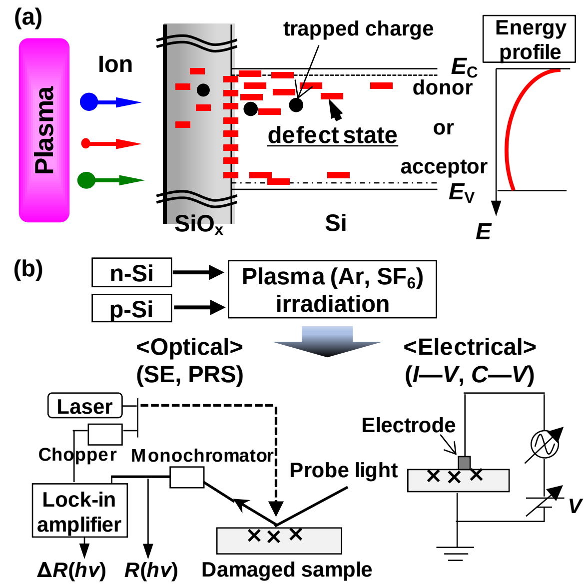

Fig. 1. (a) Schematic illustration of energy band diagram of a plasma-damaged Si substrate. (b) Experimental procedure and measurement setups employed in this study.

3. Results and Discussion

3.1 Optical Characterization

Figure 2 shows pseudo-extinction coefficient <*k*> spectra of the damaged n- and p-type Si substrates, indicating the presence of photon-absorbing sites in the bandgap. <*k*> was found to be independent of the substrate types for each process condition. This result suggests that the SE cannot identify the polarity of defects created by the plasma exposure.

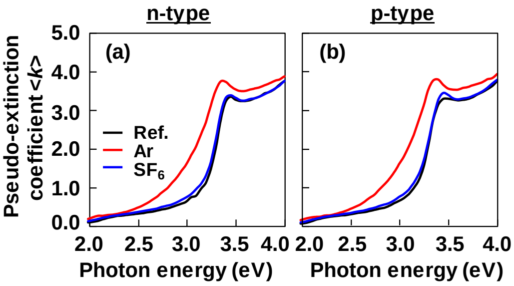

Fig. 2. Pseudo-extinction coefficient spectra of damaged (a) n- and (b) p-type Si substrates.

Figures 3(a) and (b) show PR spectra of the damaged samples. For n-type Si substrates, the peak intensity drastically decreases after Ar and SF_6 plasma exposures. In contrast, the intensity increases only in the SF_6 case. Note that this feature is also confirmed in the case of Cl_2 plasma. Since carrier trapping sites and trapped carriers in the created defects are mainly responsible for the PR spectrum change, this result implies that the "polarity" of defects—modulating that of Si substrates—depends on PID, i.e., plasma gas chemistries in this study. Figure 3(c) shows the pressure dependence of PR spectra of p-type Si substrates exposed to SF_6 plasma. No clear pressure dependence of the peak intensity was seen. This result implies the presence of the defects playing a role as carrier trapping sites. Moreover, in terms of the sensitivity of PID assessment, the usage of p-type Si substrate is preferable for an in-situ PRS analysis.

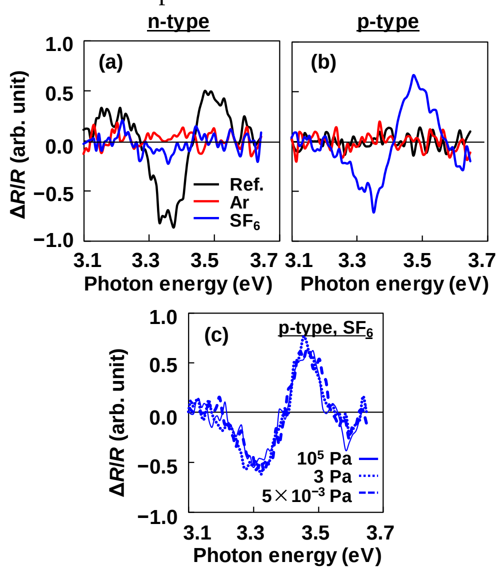

Fig. 3. PR spectra for damaged (a) n- and (b) p-type Si substrates. (c) PR spectra as a function of vacuum pressure for p-type Si substrates exposed to SF_6 plasma.

3.2 Electrical Characterization

Figures 4(a) and (b) show *I*—*V* curves of the damaged devices. These results indicate that there exist a number of n-type-like defect states, which forms a pseudo n-p junction on the p-type Si surface. Figures 4(c) and (d) show f_{mod}-dependent *C*—*V* curves of MOS structures in the case of SF_6 plasma. Both vertical and horizontal f_{mod} dispersions are observable. This feature implies that some portion of defects exist on the valence band side, which is supported by first-principle calculations [6]. The energy profile as well as the polarity of defect states in the bandgap can be identified from the *C*—*V* curves using both n- and p-type substrates.

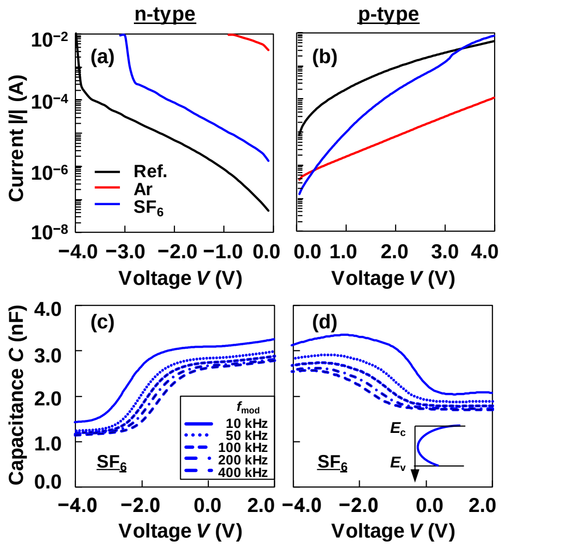

Fig. 4. (a)(b) *I*—*V* curves of damaged devices. (c)(d) f_{mod} dependences of *C*—*V* curves of MOS structures exposed to SF_6 plasma.

Figure 5 illustrates the assigned features of PID after Ar and SF_6 plasma exposures. Each characterization method has different sensitivity in the assessment of unique gas chemistry-dependences of the polarity of defects, in other words, one can improve the PID evaluation sensitivity using an optimized structure (e.g. n- or p-type) in accordance with the plasma conditions employed.

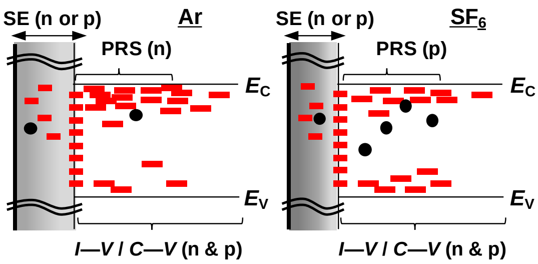

Fig. 5. Gas chemistry-dependent defect polarity. One should implement this PID feature in designing device performance.

4. Conclusions

We proposed an optimized methodology to improve the sensitivity of PID characterization methods. It was clarified that the electrical polarity of created defects significantly depends on the plasma gas chemistries. This framework is effective for design and fabrication of high performance semiconductor devices with low defect density.

Acknowledgements

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References

[1] K. Eriguchi, Jpn. J. Appl. Phys. **56** (2017) 06HA01.
[2] T. Hamano *et al*., J. Phys D **52** (2019) 455102.
[3] T. Hamano *et al*., SISPAD (2020) submitted.
[4] Y. Sato *et al*., J. Vac. Sci. Technol. B **38** (2020) 012205.
[5] J. P. Carrère *et al*., IRPS (2014) 3C.1.1.
[6] Y. Yoshikawa *et al*., Jpn. J. Appl. Phys. **57** (2018) 06JD04.