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Effects of Variability in Plasma-Induced Damage to Si Substrate on Device Performance and Its Application to Variability Assessment Methodology

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Abstract

This paper discusses the variability of defect profile induced by plasma processing and its impact on device performance. The spatial- and energy-profile variations were focused on. It was found that their variability effects show individual impacts on device characteristics. On the basis of the unique feature, we propose a sensitive method for the variability evaluation. Detailed characteristics of plasma-induced defect variability should be implemented into plasma process and device designs.

1. Introduction

Plasma processing is a key technology which realizes the state-of-the-art semiconductor devices. Although plasma processing enables to fabricate fine complicated structures, unexpected defects are created during the processes inside materials—plasma-induced damage (PID) [1]. PID has become one of the critical issues because it significantly degrades the performance and reliability of devices. It was reported [2] that the variation of plasma parameters induces that of the topological feature profiles, leading to the enhancement of device parameter variability in addition to "random dopant fluctuation" [3]. Recently, the spatial and energy profiles in addition to the number of defects were found to significantly impact device characteristics [4]. However, there have been few studies on the impacts of the spatial and energy profiles of created defects. In this study, PID in Si substrate was focused on. The defect profile was exactly redefined and the implication of the profile variability is discussed. The basic variability feature was predicted based on a molecular dynamic (MD) simulation and a first-principle calculation. We carried out model predictions of capacitance–voltage (C—V) characteristic of metal–oxide–semiconductor (MOS) capacitor as an example of a typical device. Several scenarios were assumed and variations in C—V characteristics due to the variability of the defect profile were discussed. Finally, we propose a sensitive variability assessment methodology.

2. Variability of Defect Profile in Si Substrate

2.1 Defect Profile in Si Substrate

In fabrication of the gate of MOS devices, the Si substrate is exposed to plasma and the damaged structure is created primarily due to ion bombardments. The structure consists of a surface damaged layer and a layer including local latent defects as shown in Fig. 1. Some of latent defects remain even after the following wet chemical etching and play a role as carrier trapping and detrapping sites. The latent defect is characterized by both its spatial position and energy level in the Si bandgap. Therefore, considering the accumulation of individual defect creation in the Si substrate, "the defect profile" is expressed by,

$$n_{\mathrm{dam}}(x,E)=n_{\mathrm{dam}}(x)\cdot f_{\mathrm{dam}}(E,x), \qquad (1)$$

where $n_{\mathrm{dam}}(x)$ is the spatial (depth) profiles of the defect density and $f_{\mathrm{dam}}(E, x)$ is the energy distribution function of the defect level—the energy profile of defects—in the Si bandgap at depth x, respectively. $f_{\mathrm{dam}}(E, x)$ is normalized as,

$$\int_{E_{\mathrm{V}}}^{E_{\mathrm{C}}} f_{\mathrm{dam}}(E,x)dE=1, \qquad (2)$$

where E_{c} and E_{v} are the energies of the conduction and valence bands, respectively. Therefore, in terms of the variability of "the defect profile", one has to consider both $\Delta n_{\mathrm{dam}}(x)$ and $\Delta f_{\mathrm{dam}}(E, x)$.

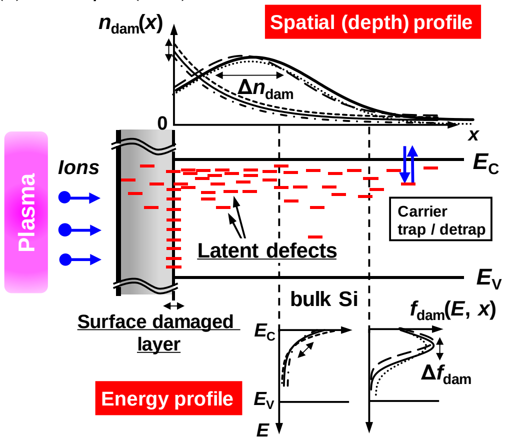

Fig. 1. Damaged structure created in a Si substrate—surface damaged layer and latent defects. Latent defects are characterized by both spatial and energy profiles. Variation in the profile of latent defects is focused on in this study.

2.2 Prediction of Defect Profile Variability

The variability of $n_{\mathrm{dam}}(x)$—$\Delta n_{\mathrm{dam}}(x)$—can be predicted by the results of MD simulations. $n_{\mathrm{dam}}(x)$ is strongly dependent on the ion energy, ion dose, and incident species. This fact implies that the "statistical" variation in $n_{\mathrm{dam}}(x)$ is induced by a series of "stochastic" defect creation due to the process parameter variation. Regarding $\Delta f_{\mathrm{dam}}(E, x)$, we employ first-principle calculations. Density-of-states are calculated assuming the structure with displaced Si atoms that is one of the typical PID structures. Figure 2 shows the variation in the width of the Si bandgap for various arrangements of displaced Si in the lattice. The width of the Si bandgap is found to strongly depend on the configuration of the damaged structure, which implies the $f_{\mathrm{dam}}(E, x)$ induces considerable variability as well as $n_{\mathrm{dam}}(x)$.

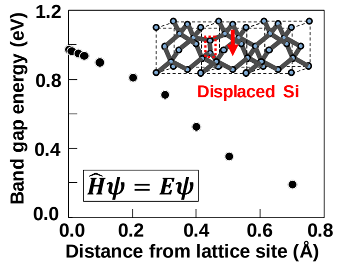

Fig. 2. Variation in the width of the Si bandgap for various arrangements of displaced Si in the lattice predicted by the first-principle calculation.

3. Variations in Capacitance–Voltage Characteristics of MOS Capacitor

Impacts of the defect profile variability on device characteristics are discussed from three viewpoints focusing on *C*—*V* characteristics of MOS capacitors.

3.1 Effects of Spatial Profile of Defects

The spatial profile $n_{\mathrm{dam}}(x)$ is assumed to be an exponential distribution expressed by,

$$n_{\mathrm{dam}}(x) = n_0 \exp\left(-\frac{x}{\lambda_{\mathrm{dam}}}\right), \tag{3}$$

where n_0 is the peak density and λ_{dam} is the characteristic depth. Figure 3(a) shows the deviation in *C*—*V* characteristics where λ_{dam} obeys a Gaussian distribution (μ, σ^2) = (5.0, 0.4^2). *C*—*V* curves shift to the horizontal direction as the λ_{dam} value varies. Figure 3(b) shows the band-voltage-shift deviation from the average curve (ΔV_{b}) for 10^6 MOS devices. The distribution of ΔV_{b} is clarified to be asymmetric, *i.e.*, the distribution tail extends only to one side, even though the variation of λ_{dam} is symmetric. This asymmetric feature should be implemented into the device-variability designs.

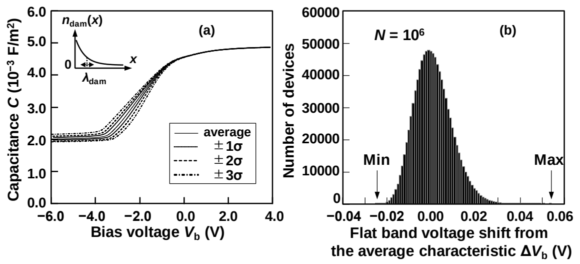

Fig. 3. (a) Predicted deviation in *C*—*V* characteristic due to the variability of $n_{\mathrm{dam}}(x)$. (b) Predicted distribution of flat band voltage shift from the average characteristic (solid line in (a)).

3.2 Effects of Energy Profile of Defects

The energy profile of defects $f_{\mathrm{dam}}(E, x)$ is assumed to be a Gaussian-type distribution expressed by,

$$f_{\mathrm{dam}}(E, x) \propto \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{E}}} \exp\left[-\frac{\left(E-\overline{E}\right)^2}{{\sigma_{\mathrm{E}}}^2}\right], \tag{4}$$

where $\overline{E}$ and σ_{E} are the average energy level of defects and the variance, respectively. Note that the validity of the assumed energy profile is confirmed by simulation and experiment [5]. Figure 4 shows the deviation in *C*—*V* characteristics where $\overline{E}$ obeys a Gaussian distribution (μ, σ^2) = (0.9, 0.05^2). As $|\Delta f_{\mathrm{dam}}(E, x)|$ increases, the deviation of *C*—*V* curve exhibits unique features—the appearance of "hump". This implies that the distortion of the *C*—*V* curve can be used as a measure of the variability evaluation of $f_{\mathrm{dam}}(E, x)$.

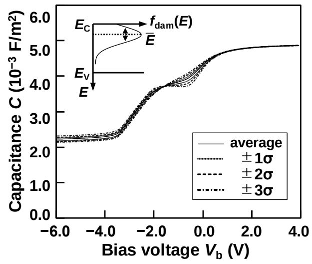

Fig. 4. Predicted deviation in *C*—*V* characteristics due to the variability of the energy profile of defects $f_{\mathrm{dam}}(E, x)$.

3.3 Application to Variability Evaluation Method

As pointed out [6], the *C*—*V* curve of a PID sample strongly depends on the modulation frequency f_{mod}. Figure 5(a) shows the variation of *C*—*V* curves for a p-type Si substrate exposed to Ar plasma, where the energy level of defects is located near the conduction band. Figure 5(b) shows the predicted variation in *C*—*V* curves in the case f_{mod} = 10 and 100 kHz due to the presence of $\Delta n_{\mathrm{dam}}(x)$. The variation is found to be much larger for 100 kHz than that for 10 kHz with the same $\Delta n_{\mathrm{dam}}(x)$. Thus, one can evaluate with high sensitivity the variability enhancement by PID with respect to $\Delta C/C$ by optimizing f_{opt} as shown in the inset of Fig. 5(b).

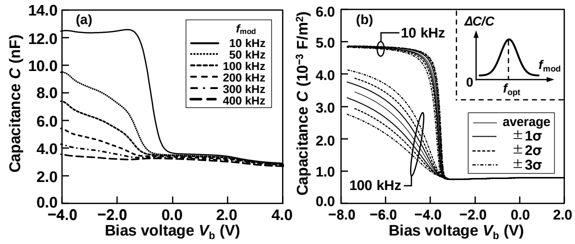

Fig. 5. (a) Experimental modulation frequency f_{mod} dependence of *C*—*V* curves of a p-type Si substrate after Ar plasma exposure [6]. (b) Predicted variation in the *C*—*V* curves for two different f_{mod}.

4. Conclusions

We investigated the impacts of the variability of the spatial and energy profiles of defects on device characteristics. Model prediction clarified that the *C*—*V* characteristics and the estimated ΔV_{b} were strongly affected by PID variability. We proposed a sensitive variability evaluation method utilizing the unique f_{mod} dependence of *C*—*V* curves. Present findings imply that the detailed assessment of PID variability is essential for designing plasma process and device.

Acknowledgements

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