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Improved Conductance Method for Interface Trap Density of ZrO_2-Si interface

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Abstract

We propose a new conductance method which considered the multi centroids of trap distribution to extract interface trap density, D_{it}, of a MOS capacitor. In this work, we have prepared n-type MOS capacitor samples comprising of ZrO_2 with a metal gate. By analyzing measured C-V characteristics with this new method, we find that the extracted D_{it} is discrete in the spectrum inside a forbidden gap and then successfully characterize the interface trap levels.

1. Introduction

It has been an important engineering topic to characterize interface trap density (D_{it}) in MOS capacitors with electrical measurement [1-7]. The conductance method [1-5] has been extensively used to extract detailed information of dangling bond interface states. However, since it assumes a continuous D_{it}, the total quantity of interface states (integrated D_{it}) is likely overestimated due to the overlap response in G-V characteristics, where G and V stand for conductance and voltage, respectively. Hence, it is demanded to propose a revised conductance method which can validate a discrete D_{it}.

2. Theory and model

The conductance method for p-type is revised from [1] and formulated by the equation:

$$\frac{G_P}{\omega} = \frac{qD_{it}(2\pi\sigma_s{}^2)^{-\frac{1}{2}}}{2\xi}\int_{-\infty}^{\infty}(\exp[-\frac{\eta_v{}^2}{2\sigma_s{}^2}] \cdot \exp(\eta_v)\ln(1+\xi^2\exp(-2\eta_v))d\eta_v, \quad (1)$$

where ω is an angular frequency and $\xi = \omega\tau_n$ with τ_n being an electron time constant and G_P is a parallel conductance having a band bending fluctuation around average: $\eta_v = v_s - < v_s >$ with $v_s = (E_i(0) - E_i(\infty))/k_BT$ and σ_s being a standard deviation. The $E_i(0)$ and $E_i(\infty)$ are intrinsic Fermi levels at oxide-Si interface and in bulk, respectively.

In the conventional conductance method [1], this η_v is not related to trap level E_T explicitly. Therefore, we replace η_v with: $\eta_\mu = \mu_s - < \mu_s >$, where $\mu_s = (E_T - E_C)/k_BT$ with E_C being the conduction band edge and σ_s becoming a standard deviation of η_μ. This revision is consistent to neglecting capture and emission of holes in the SRH process [8]. The revised conductance method includes a full spectrum of D_{it} in a forbidden gap, as long as $< E_T >$ equals E_F. It is self-evident that if G_P is continuous, the D_{it} is also continuous. And it is clear that we can extract D_{it} from eq. 1. However, the extracted continuous D_{it} cannot reproduce the G_P/ω properly. This is due to the overestimation of D_{it} from the overlap in the energy spectrum as shown in Fig. 1 (d). Additionally, a continuous D_{it} implies unlimited combination of interface states. We, thereby, assume a discrete D_{it} in forbidden gap:

$$\frac{G_P}{\omega} = \frac{q}{2}\sum_k \int_{-\infty}^{\infty} \frac{D_{it,k}}{\omega\tau_{n,k}} \cdot \ln\left\{1 + \left(\omega\tau_{n,k}\right)^2\right\} P\left(\eta_\mu\right) d\eta_\mu, \quad (2)$$

where $P(\eta_\mu)$ is a Gaussian distribution of η_μ. The $D_{it,k}$ and $\tau_{n,k}$ are interface trap density and electron time constant at a given energy branch k. Since we have neglected hole's process in the SRH, a dominant branch may exist near E_C in the forbidden gap.

3. Experiment

We prepare samples of n-type MOS capacitor, where the substrate doping concentration is 10^{15} cm^{-3} with ALD thicknesses of ZrO_2 being 6.4 nm and 19.2 nm. We used LCR meter in parallel mode and at various frequencies to measure C-V and G-V characteristics, respectively, where C stands for capacitance. To obtain G_P, we use eq. (3) [1]:

$$\frac{G_P}{\omega} = \frac{\omega C_{ox}{}^2 G_m}{G_m{}^2 + \omega^2(C_{ox} - C_m)^2}. \quad (3)$$

The C_{ox}, C_m and G_m are oxide capacitance, measured capacitance and measured conductance, respectively.

4. Result and discussion

The line with squares in Fig. 1 (a) and (b) stand for the measured spectrum of G_P/ω, where ZrO_2 thickness is 6.4 nm at 250 mV and 300 mV, respectively. We assume fast and slow branches with short and long τ_n in eq. (2), to comprise a superposition, of fast and slow branches, as plotted with the dotted lines, respectively. This superposition exhibits an excellent agreement with the measured spectrum. Subsequently, we use eq. (1) to extract D_{it} from the spectrum of G_P/ω. In Fig. 1 (c), we plot the extracted D_{it} with green line. We select several points of this D_{it} (red crosses in Fig. 1 (c)) and then plot the superposition with violet dotted line in Fig. 1 (d). However, this fails to fit the measurement (blue line with squares). In Fig. 2, we compare the extracted D_{it} with eqs. (1) and (2). Note that eq. (2) results in a discrete D_{it} while eq. (1) leads to a continuous D_{it}. The left of Fig. 3 illustrates band diagram for 6.4 nm ZrO_2. In the right, the discrete D_{it} exhibits a small deviation between 250 mV and 300 mV. This implies that the same traps respond in the spectrum.

Similarly, the lines with squares in Fig. 4 stand for the measured spectrum of G_P/ω, where ZrO_2 thickness is 19.2 nm at 250 mV (Left) and 300 mV (Right). The superposition comprising slow, middle, and fast in eq. (2) exhibits an excellent agreement with the measured spectrum, as plotted with dotted lines. Note that the spectrum is asymmetry regarding frequency, which can be reproduced by eq. (2) but not by eq. (1). Subsequently, the D_{it} is obtained through this superposition, as plotted with marks in Fig. 5. There are also lines with marks, obtained with eq. (1), for the comparison. The left of Fig. 6 illustrates band diagram for 19.2 nm ZrO_2. In the right, the discrete D_{it} exhibits a small deviation between 250 mV and 300 mV. This implies that the same traps respond in the spectrum.

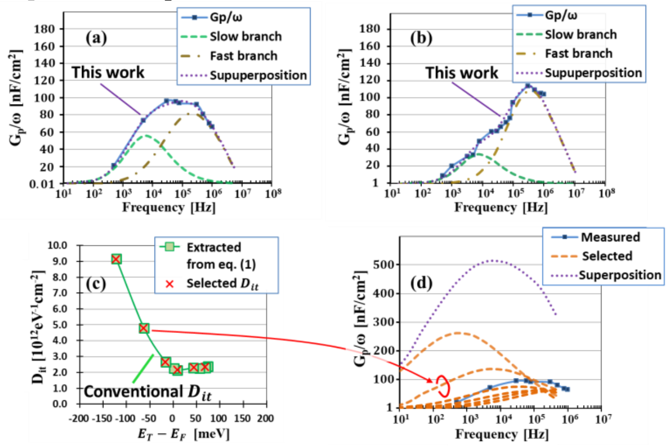

Fig. 1 The G_P/ω spectrum for ZrO_2 thickness 6.4 nm at (a) 250 mV and (b) 300 mV; (c) the extracted D_{it} by eq. (1); (d) the comparison of measured G_P/ω and deduced one by eq. (1).

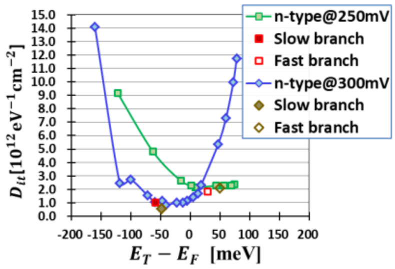

Fig. 2 The extracted D_{it} for ZrO_2 thickness 6.4 nm at 250 mV and 300 mV; the line with squares and the squares respectively stand for data obtained by eq. (1) and eq. (2) at 250 mV; the line with diamonds and the diamonds respectively stand for data obtained by eq. (1) and eq. (2) at 300 mV.

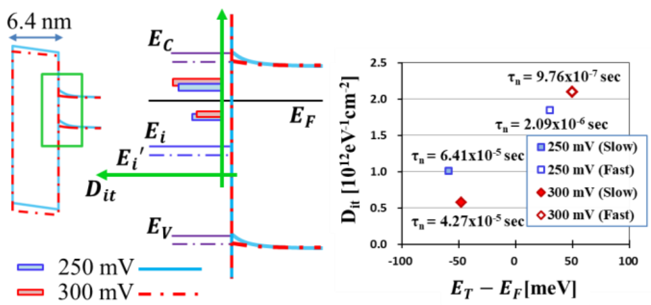

Fig. 3 Band diagram of ZrO_2 with thickness being 6.4 nm at 250 mV and 300 mV with discrete D_{it} obtained with eq. (2).

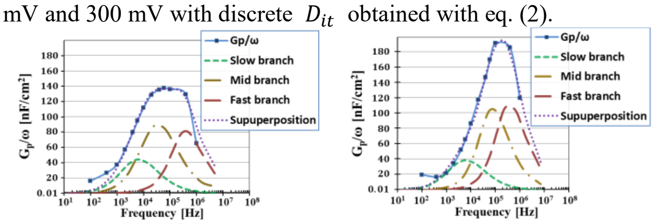

Fig. 4 The G_P/ω spectrum of ZrO_2 thickness being 19.2 nm at 250 mV (Left) and 300 mV (Right); the green, brown and garnet lines respectively stand for slow, middle and fast branches.

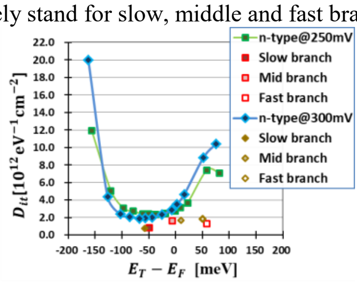

Fig. 5 The extracted D_{it} of ZrO_2 thickness being 19.2 nm at 250 mV and 300 mV; the lines with squares and the squares respectively stand for data obtained by eq. (1) and eq. (2) at 250 mV; the line with diamonds and the diamonds respectively stand for data obtained by eq. (1) and by eq. (2) at 300 mV.

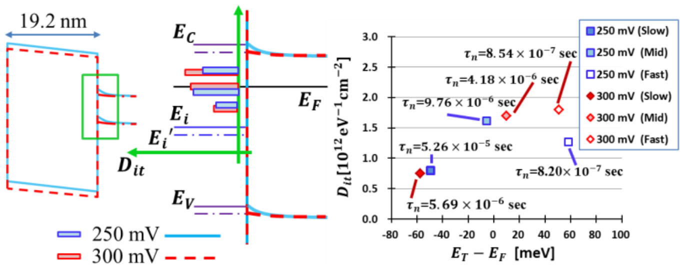

Fig. 6 Band diagram of ZrO_2 thickness 19.2 nm at 250 mV and 300 mV with discrete D_{it} obtained with eq. (2).

5. Conclusions

We have proposed a revised conductance method to extract discrete D_{it}, and we have considered that G_p/ω is comprised of a superposition of discrete branches of electron time constant. A continuous D_{it} profile obtained with the conventional conductance method cannot reproduce asymmetric spectrum of G_p/ω. Our revised conductance method is helpful for quantitative investigation of interface states.

6. Acknowledgment

Tokyo Electron Technology Solutions Limited fabricated the ZrO_2 gate insulator film. The fluctuation-free facility in Tohoku University. carried out the remaining processes to fabricate the MOS capacitor samples from this ZrO_2 film. Then, we performed the electrically characterization of these samples.

References

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