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Characterization of Interface States in MOS Systems by Using Photonic High-Frequency Capacitance-Voltage Responses

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Based on the photonic high-frequency capacitance-voltage response of Metal-Oxide-Semiconductor capacitors, we report an improved characterization method for the analyzing of interface states in MOS systems. An optical source with a photonic energy $E_{ph} = 0.943$ eV ($\lambda = 1314.5$ nm) is employed for photonic deep-depletion (fast sweep rate) high-frequency Capacitance-Voltage (photonic DD HF-CV) characterization of interface states distributed in the photo-responsive energy band. Using the photonic DD HF-CV characterization, we obtained a U-shaped distribution of D_{it} over $(E_V + E_g/2 - q\phi_f) < E_t < (E_V + E_g/2 - q\phi_f + q\phi_S)$ for N-type Metal-Oxide-Semiconductor capacitors and $(E_C - E_g/2 - q\phi_f + q\phi_S) < E_t < (E_C - E_g/2 - q\phi_f)$ for P-type Metal-Oxide-Semiconductor capacitors.

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I. INTRODUCTION

Interface states at the Si/SiO_2 heterojunction in a Metal-Oxide-Semiconductor structure play a crucial role in determining the electrical characteristics of Metal-Oxide-Semiconductor Field-Effect-Transistors [1, 2], which include the threshold voltage (V_T), the channel carrier mobility (μ), the transconductance (g_m), and the subthreshold slope (S). Accurate characterization of interface states throughout the band gap is, therefore, very important for improving the robustness of devices and their integrated circuits with MOS capacitors and MOSFETs. Including the charge-pumping method, and deep level transient spectroscopy (DLTS), there have been enormous efforts to characterize the interface states in MOS capacitors and MOSFETs [2–5]. In this work, we report a new model and experimental results for the photonic deep-depletion high-frequency capacitance-voltage (DD HF-CV) characteristics when the photon energy (E_{ph}) is less than the silicon band gap energy (E_g).

II. INTERFACE STATE CHARACTERIZATION USING THE PHOTONIC HIGH FREQUENCY C-V CHARACTERISTICS OF MOS CAPACITORS

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As shown in Fig. 1, the photonic HF-CV characteristics of MOS capacitors with $t_{ox} = 23$ nm and $W \times L = 300\times300\ \mu m^2$ were measured for a small signal frequency, $f = 500$ kHz, and at a slow DC sweep rate, 1 mV/s. Due to the limited contribution of photogenerated excess channel carriers only from the interface states at the Si/SiO_2 interface under illumination with light having a wavelength of $\lambda = 1314.5$ nm, the gate capacitance in the inversion mode ($|V_G|>|V_T|$) increases little and shows a negligible variation with increasing optical power (P_{opt}). However, due to the abundant contribution of photogenerated excess carriers from the valence band to the conduction band under irradiation at a wavelength of λ = 850 nm, the gate capacitance in the inversion region is significantly increased, but its variation with increasing P_{opt} is negligible. Therefore, the slow sweep-rate HF-CV characteristics of a MOS capacitor under optical illumination is not suitable for the characterization when $E_{ph} > E_g$ or $E_{ph} < E_g$.

The photonic DD HF-CV characteristics were measured with the same small signal-frequency, $f = 500$ kHz, and fast DC sweep rate, 50 mV/s. The equivalent circuit model of a MOS capacitor under deep-depletion high-frequency conditions can be described by

$$\frac{1}{C_G} = \frac{1}{C_{OX}} + \frac{1}{C_d} \quad (1)$$

with an equivalent model as shown in Fig. 2 [6]. Without an optical input, we may assume $C_{OI} = C_{OT} = 0$. The

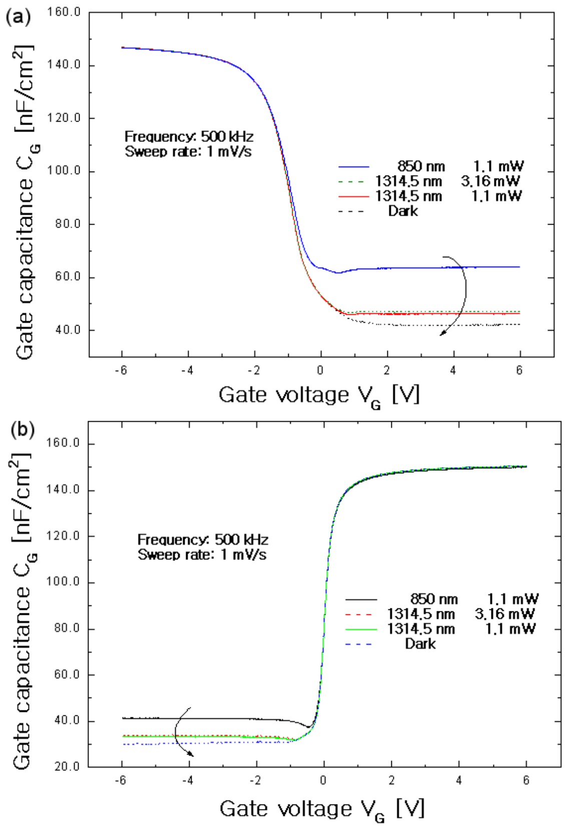

Fig. 1. Photonic HF-CV characteristics of MOS capacitors under optical illumination (λ = 1314.5 nm, 850 nm): (a) NMOS capacitor and (b) PMOS capacitor.

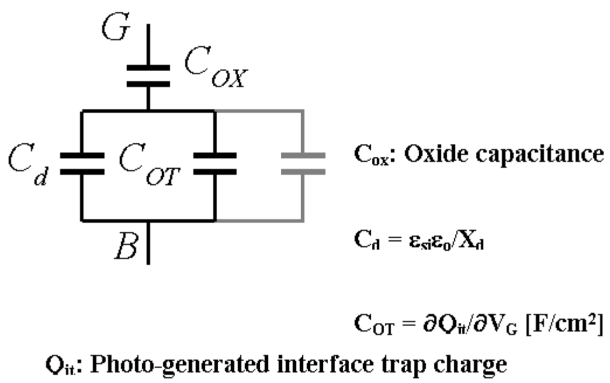

Fig. 2. Equivalent circuit of MOS capacitors under DD HF measurement conditions.

surface potential (ϕ_s), which is described by

$$\phi_s = \pm\frac{qN_b\epsilon_{si}\epsilon_0}{2}\left(\frac{C_{OX}-C_G}{C_{OX}C_G}\right)^2, \quad (2)$$

can be obtained from the measured DD HF-CV curve as a function of the gate bias. Extracted surface potentials for P- and N-MOS capacitors are shown in Fig. 3.

Photonic DD HF-CV curves for an optical input with λ = 1314.5 nm are shown in Fig. 4. Due to the photo-

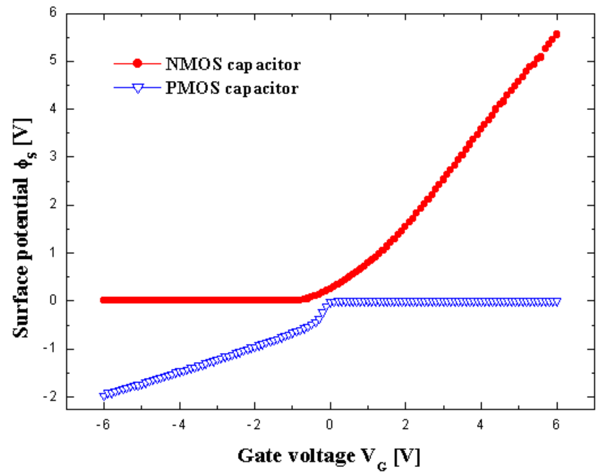

Fig. 3. Surface potential of a MOS capacitor under DD HF conditions.

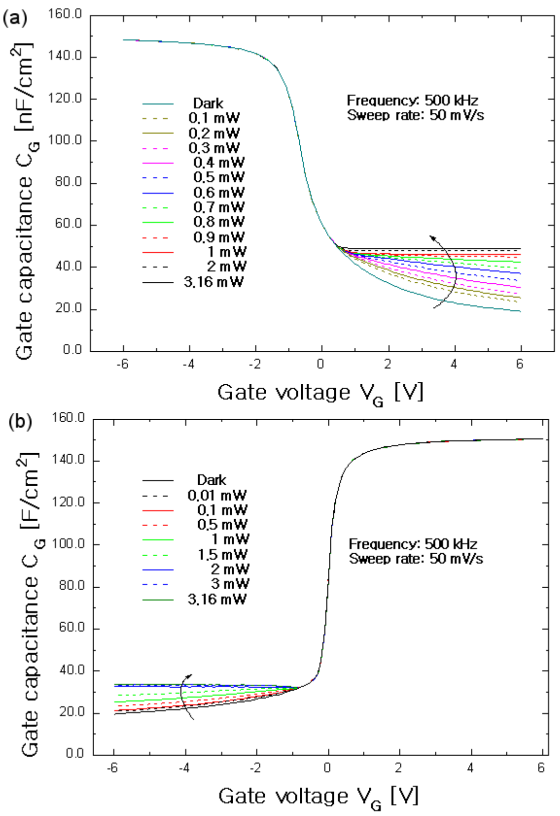

Fig. 4. Photonic DD HF-CV characteristics with λ = 1314.5 nm: (a) NMOS capacitor and (b) PMOS capacitor.

generation and to the contribution of excess carriers excited from the interface states at the Si/SiO_2 interface, the gate capacitance in the inversion region increases with increasing P_{opt}. Under a fast DC sweep rate (50 mV/s), which is fast enough that the ramping time is shorter than the minority-carrier response time, insufficient time exists for the photogenerated excess carriers

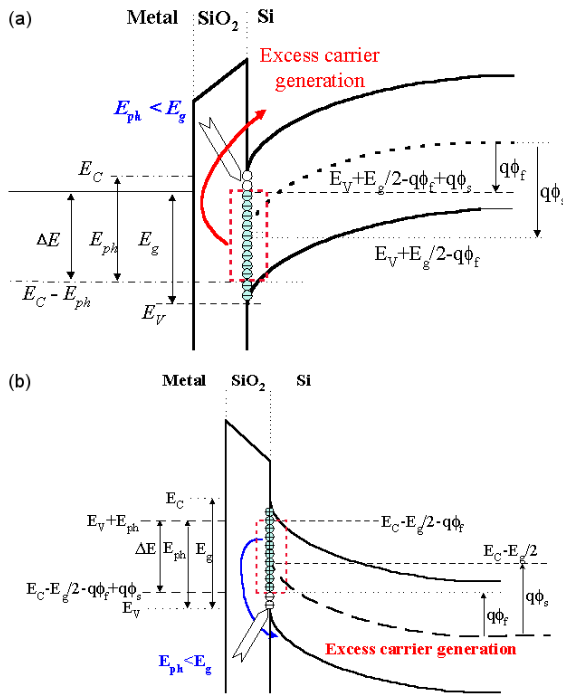

Fig. 5. Energy band diagram of MOS capacitors under optical illumination: (a) NMOS capacitor and (b) PMOS capacitor.

to form an inversion layer [7]. Thus, we can minimize the unnecessary modulation of interface states caused by the measurement signal (small ac signal and DC sweep voltage) and observe the change in the photonic DD HF-CV curve caused by the optically excited carriers from only the interface states in the photo-responsive energy band. Therefore, the gate capacitance under an optical input with $\lambda = 1314.5$ nm is described by

$$C_{GO} = \frac{C_{OX}(C_d + C_{OT})}{C_{OX} + C_d + C_{OT}}, \tag{3}$$

where C_d is the depletion capacitance without photo-illumination. From Eq. (3), the capacitance C_{OT}, caused by the photogenerated carriers from the interface states under an optical input, is given by

$$C_{OT} = \frac{C_{OX}C_d - C_{GO}(C_{OX} + C_d)}{C_{GO} - C_{OX}}. \tag{4}$$

C_{OT} can also be obtained from

$$C_{OT} = \frac{\partial Q_{it}}{\partial V_G} = \frac{\partial Q_{it}}{\partial \phi_S}\frac{\partial \phi_S}{\partial V_G}, \tag{5}$$

where $\partial Q_{it}/\partial \phi_S$ is defined as C_{it}. From Eq. (5) under optical illumination, we get the capacitance C_{it} ($\partial Q_{it}/\partial \phi_S$) which is solely contributed by the interface states at $E_t = E_V + E_g/2 - q\phi_f + q\phi_S$ for NMOS capacitors and at $E_t = E_C - (E_g/2 + q\phi_f) + q\phi_S$ for PMOS capacitors. The extracted C_{it} is shown in Fig. 5 for N- and P-MOS capacitors. Using the above derivation, we obtain a distribution of the interface state density D_{it} which can be described by [2]

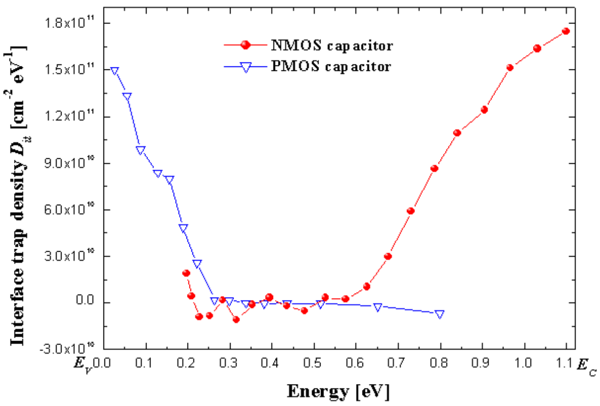

Fig. 6. Interface trap density in NMOS and PMOS capacitors.

$$D_{it} = \frac{C_{it}}{q}. \tag{6}$$

As shown in Figure 6, by using the photonic DD HF-CV curve, we obtained a U-shaped distribution [1] for D_{it} ($\sim 1.7\times10^{11}$ cm^{-2}eV^{-1} at E_C and E_V) over the photo-responsive energy ranges $(E_V + E_g/2 - q\phi_f) < E_t < (E_V + E_g/2 - q\phi_f + q\phi_S)$ for N-MOS capacitors and $(E_C - E_g/2 - q\phi_f + q\phi_S) < E_t < (E_C - E_g/2 - q\phi_f)$ for P-MOS capacitors. We note that the photo-responsive energy range is not $(E_C - E_{ph}) < E_t < (E_V + E_g/2 - q\phi_f + q\phi_S)$, but $(E_V + E_g/2 - q\phi_f) < E_t < (E_V + E_g/2 - q\phi_f + q\phi_S)$, to keep the surface potential $\phi_S \geq 0$ for N-MOS capacitors. This also applies to P-MOS capacitors to keep $\phi_S \leq 0$ in the characterization.

As supporting data for the effectiveness of the photonic DD HF-CV method with $E_{ph} < E_g$, we characterized MOS capacitors with E_{ph} ($\lambda = 850$ nm) $> E_g$ and we show the result in Fig. 7. Contrary to the C-V characteristics obtained for $\lambda = 1314.5$ nm with the same measurement setup, DD HF-CV characteristics are predominantly controlled by the excess carriers from the band-to-band photogeneration in the bulk ($E_{ph} > E_g$). The photonic DD HF-CV response of the interface states under an optical input with $\lambda = 850$ nm is fully screened by the abundant photogenerated excess inversion carriers. Therefore, photonic the DD HF-CV response and its physical mechanisms caused by the interface states are only observed in the characterization with $\lambda = 1314.5$ nm. Therefore, we conclude that the DD HF-CV characteristics under an optical input are mainly governed by the photogenerated excess carriers from the interface states; therefore, the DD HF-CV response is effective for the characterization of D_{it} in MOS capacitors.

III. CONCLUSION

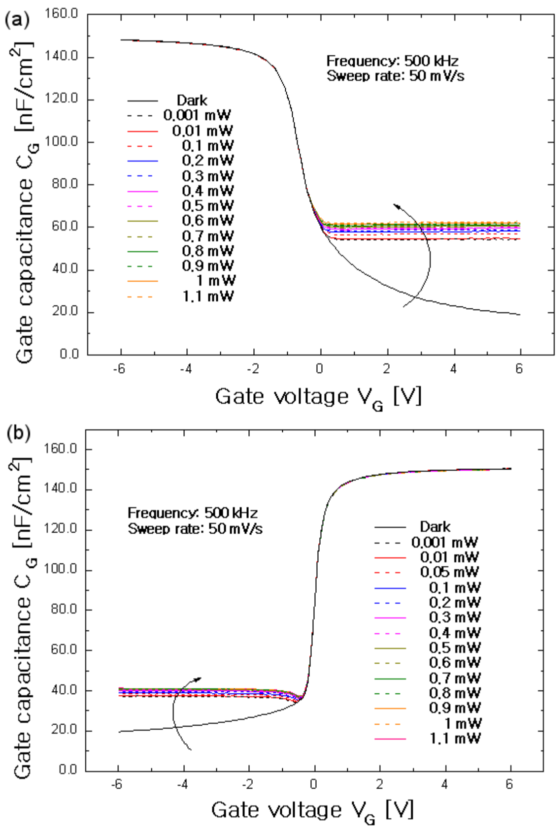

Fig. 7. Photonic DD HF-CV characteristics with λ = 850 nm: (a) NMOS capacitor and (b) PMOS capacitor.

Based on the photonic deep-depletion high-frequency C-V characteristics of MOS capacitors under an optical input with λ = 1314.5 nm, we obtained a U-shaped distribution for D_{it} in the photo-responsive energy range. we believe that the photonic DD HF-CV method to be useful for characterizing the interface states in the Si/SiO_2 interface.

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