Photonic Characterization of Capacitance-Voltage Characteristics in MOS Capacitors and Current-Voltage Characteristics in MOSFETs


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I. INTRODUCTION

Interface states at the SiO$_2$/Si heterojunction in MOS structures play a crucial role in determining the threshold voltage ($V_T$), the channel carrier mobility ($\mu$), the transconductance ($g_m$), and the other electrical performance of MOSFETs [1,2]. Therefore, accurate modeling and characterization of interface states throughout the band-gap are the most important topics for improving the robustness of devices and their integrated circuits with MOS capacitors and MOSFETs. There has been an enormous effort on accurate characterization of interface traps in MOS capacitors and MOSFETs [3–10]. However, almost all of the previous methods require a complicated measurement procedure or destructive characterization methods [7].

In this paper, for efficient and accurate analysis of interface traps in MOS capacitors and MOSFETs, we propose a new non-destructive method that combines photoresponsive capacitance-voltage (photonic C-V) and current-voltage (photonic I-V) characteristics with a photonic energy less than the silicon band-gap energy ($h\nu < E_g$). Distribution of interface states at the SiO$_2$/Si heterojunction in MOS structures are investigated by using the new photonic C-V method for characterizing the interface states in the energy bandgap (NMOS: $E_C - h\nu \leq E \leq E_C$, PMOS: $E_V \leq E \leq E_V + h\nu$).

II. PHOTORESPONSIVE CHARACTERIZATION MOS CAPACITORS AND MOSFETS

Photoresponsive high-frequency capacitance-voltage (photonic HF-CV) characteristics of MOS capacitors and photoresponsive current-voltage (photonic I-V) characteristics of MOSFETs are measured by illuminating a photoresponsive absorption region (gate terminal) with two different optical sources ($\lambda = 1314.5$ nm and 1551 nm). In order to prevent band-to-band excitation from the silicon substrate and to address photocexcitation of excess carriers only from the SiO$_2$/Si interface states, we applied incident optical sources with a photonic energies ($h\nu = 0.799$ and 0.943 eV) less than the silicon band-gap energy ($E_g = 1.11$ eV) to the device under test. Characterization of MOS capacitors was performed on a wafer with an optical input (ILX Lightwave Technology model 7800D multi-channel fiber optic source, FP: $P_{opt}$: optical power) via a cleaved multimode optical fiber (illumination diameter $\sim 200$ $\mu$m). We note that there was no anti-reflection coating on the surface of MOS capacitors under test; therefore, the absolute value of the optical power delivered to the device under test could be different from $P_{opt}$. Photonic HF-CV characteristics of N-MOS capacitors with $W \times L = 300 \times 300$ $\mu$m$^2$ were measured under a specific condition (frequency: 500 kHz, DC voltage sweep rate: 0.05 V/s, step: 120) with optical illumination. The measured photonic C-V characteristics and the surface potential for $\lambda = 1314.5$ and 1551 nm are shown in Fig. 1. It is seen from Fig. 1 (a) that the high-frequency capacitance of the device is significantly modulated by the incident photonic excitation for $V_G \geq 0$ (depletion mode $\sim$ inversion mode of gate bias).

For a quantitative interpretation of the experimental data, we introduce a one-dimensional Poisson’s equation and charge distribution in the vertical direction to the
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Fig. 1. Photonic response of an N-MOS: (a) gate capacitance (b) surface potential.

MOS capacitors under illumination that is described by

\[ \nabla^2 \phi_L = - \left( \frac{\rho_L}{\epsilon_o \epsilon_{si}} \right) \]  

and

\[ \rho_L = q \left[ N_d - N_a + p_o \exp \left( -\frac{\phi_L}{V_{th}} \right) \right. \]

\[ \left. - (n_o + \Delta n) \exp \left( \frac{\phi_L}{V_{th}} \right) \right] , \]  

where \( \phi_L [V] \) is the potential at any point under illumination, \( \rho_L [C/cm^3] \) is the charge density, \( N_d \) (\( N_a \)) \( [cm^{-3}] \) is the ionized donor (acceptor) density in the substrate, \( \epsilon_o \) and \( \epsilon_{si} [F/cm] \) is the dielectric constants of vacuum and silicon, respectively, and \( \Delta n [cm^{-3}] \) is the excess carrier density generated due to optical excitation from the interface states by the optical input with a photonic energy less than the silicon band-gap energy. The electric charge density \( Q_S [C/cm^2] \) per unit area in the semiconductor at the SiO\(_2\)/Si heterojunction interface under illumination can be obtained by solving Eq. (1) [11]:

\[ Q_S = - \left( \sqrt{2V_{th}\epsilon_o \epsilon_{si}} \right) \left[ V_{th} \exp \left( \frac{\phi_{SL}}{V_{th}} \right) + \phi_{SL} - V_{th} \right. \]

\[ \left. + \frac{(n_{po} + \Delta n)}{p_{po}} \left( V_{th} \exp \left( \frac{\phi_{SL}}{V_{th}} \right) - \phi_{SL} - V_{th} \right) \right]^{1/2} , \]  

where \( \phi_{SL} \) is the surface potential under illumination, \( V_{th} = kT/q \) is the thermal voltage, \( L_D \) is the Debye length, and \( n_{po} \) (\( p_{po} \)) is the inverted electron (majority hole) concentration without optical excitation.

The variation in the capacitance-voltage characteristics of the MOS capacitors under optical illumination is predominantly caused by the generation of excess carriers from the interface traps in the SiO\(_2\)/Si (trapped electrons), as shown in Fig. 2 [12,13]. We note that the incident optical input has a photonic energy less than the silicon band-gap. Photoexcited excess carriers from the interface states in the SiO\(_2\)/Si heterojunction traps induce a decrease in the surface potential (\( \phi_{SL} \)) under a constant applied voltage, as shown in Fig. 1(b). A decrease in the surface potential results in a reduction of the depletion width, which is followed by a corresponding increase of the capacitance [11]. It is also seen from Figs. 1 and 2 that the capacitance and the photoexcited interface trapped charge of the device increase more with \( \lambda = 1314.5 \) nm than with \( \lambda = 1551 \) nm because the photonic energy of \( \lambda = 1314.5 \) nm (\( h\nu = 0.943 \) eV) is larger than that of \( \lambda = 1551 \) nm (\( h\nu = 0.799 \) eV).

Figure 3 shows the dependence of the high-frequency capacitance and the surface potential on the gate voltage for various optical powers. It is found that the capacitance increases with increasing incident optical power. Figure 3 also shows a decrease in the value of the surface potential with increasing incident optical power. It is seen from Fig. 3(b), in particular, that the photonic variation of the capacitance in the device with \( \lambda = 1551 \) nm...
Fig. 3. Photonic response of N-MOS capacitors to various optical powers: (a) $\lambda = 1314.5$ nm and (b) $\lambda = 1551$ nm.

The photonic capacitance-voltage response of MOS capacitors depends strongly on the incident optical power. Photore sponsive current-voltage characteristics ($I_D - V_{GS}$, $V_{DS}$) of n-channel MOSFETs with $W/L = 30 \mu m/0.8 \mu m$ were measured under optical illumination in close proximity to the gate of the device under test, as shown in Fig. 4. Because of photonic excitation of carriers from the Si/SiO$_2$ interface traps, both the photovoltaic effect, which dominantly changes the threshold voltage, and the photoconductive effect, which increases the channel conductivity and drain current for the same electrical bias, were expected. The drain current increased under optical illumination as shown in Fig. 4 due to the increased channel carrier density and channel carrier mobility as well as a decreased threshold voltage caused by photoexcited excess carriers from the interface trapped electrons under optical illumination. These excess carriers are generated from the trap levels located in $E_C - \hbar \nu < E < E_C$ which is a photoresponsive energy band because optical sources have a photonic energy less than the silicon band-gap energy. From these experimental results, the capacitance of the MOS capacitors and the current-voltage characteristics of MOSFETs increase due to the generation of excess carriers from the interface traps under incident optical sources with a photonic energy less than silicon band-gap energy.

III. CONCLUSION

Based on the photonic capacitance-voltage response of MOS capacitors, we characterized the interface traps. Two different optical sources ($\lambda = 1314.5$ nm, $1551$ nm, $\hbar \nu \sim 1.24/\lambda(\mu m) eV$) with energies less than the silicon band-gap energy ($\hbar \nu < E_g$, $E_g = 1.12 eV$) were used in the photonic capacitance-voltage response of interface traps to a limited energy band ($E_C - \hbar \nu < E < E_C$). Photonic capacitance-voltage characteristics of N- and P-MOS capacitors with $W \times L = 300 \times 300 \mu m^2$ were investigated. The photonic variations of high-frequency capacitance-voltage (HF-CV) characteristics in N-MOS capacitors were very sensitive due to optically excited excess carriers from the interface traps under incident optical illumination with a photonic energy less than the silicon band-gap energy. Interface traps in MOS capacitors could be characterized by this new method using the measured photonic response characteristics without complicated iteration procedures or destructive methods.

In this research, interface traps at Si/SiO$_2$ interfaces in MOS capacitors and MOSFETs were investigated with photonic C-V characteristics of MOS capacitors and photonic I-V characteristics of MOSFETs. If various optical sources with photonic energies less than the silicon band-gap energy are used, the new nondestructive method is expected to be useful for efficient and accurate extraction of the interface trap density and its energy distribution, which are critical to improving high-speed performance and reliability in MOSFET and MOS integrated circuits.

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