Journal of the Korean Physical Society, Vol. 40, No. 1, January 2002, pp. 64∼67

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

H. C. Kim, H. T. Kim, S. D. Cho, S. J. Song, Y. C. Kim, S. K. Kim, S. S. Chi, D. J. Kim and D. M. Kim
School of Electrical Engineering, Kookmin University, Seoul 136-702

(Received 11 February 2001)

Based on the photonic high-frequency capacitance-voltage (HF-CV) response of MOS capacitors, a new characterization method is reported for the analysis of interface states in MOS systems. An optical source with a photonic energy less than the silicon band-gap energy ($h\nu < E_g$) is employed for the photonic HF-CV characterization of interface states distributed in the photoresponsive energy band ($E_C - h\nu < E_t < E_C$). If a uniform distribution of trap levels is assumed, the density of interface states (D_{it}) in the photoresponsive energy band of MOS capacitors, characterized by the new photonic HF-CV method, was observed to be $D_{it} = 1 \sim 5 \times 10^{11}$ eV^{-1} cm^{-2}. Photonic current-voltage characteristics ($I_D - V_{GS}$, V_{DS}) of MOSFETs, which are under control of the photoconductive and the photovoltaic effects, are also investigated under optical illumination.

PACS numbers: 72.40.+w

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 (μ), 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 (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 (λ = 1314.5 nm and 1551 nm). In order to prevent band-to-band excitation from the silicon substrate and to address photoexcitation 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 ∼200 μm). 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 × L = 300 × 300 μm^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 λ = 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 ∼ 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

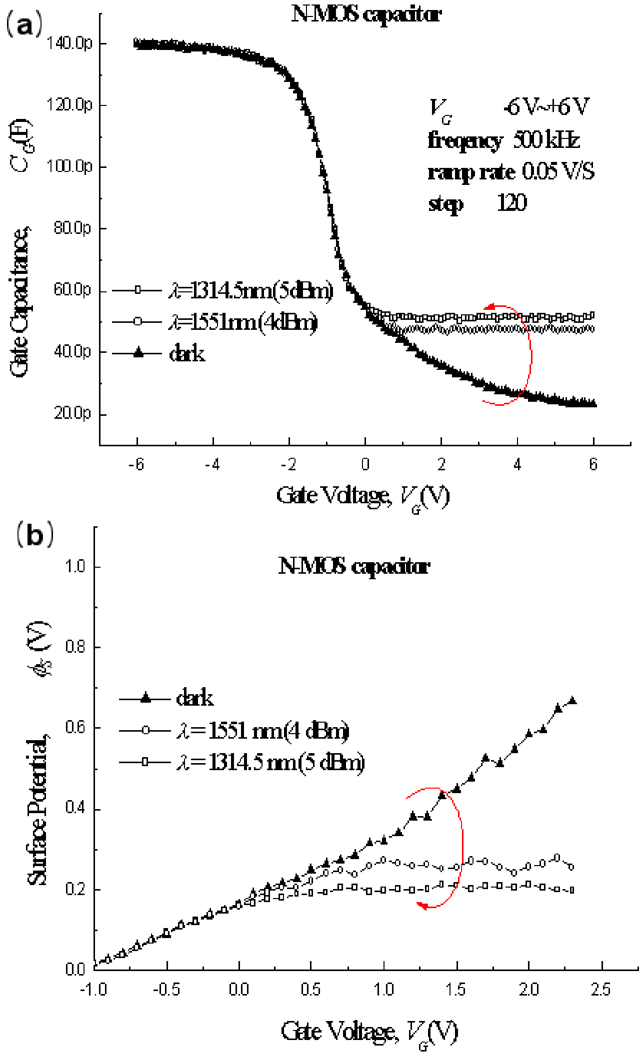

Fig. 1. Photonic response of an N-MOS: (a) gate capacitance (b) surface potential.

MOS capacitors under illumination that is described by

$$\nabla^2 \phi_L = -\left(\frac{\rho_L}{\epsilon_o \epsilon_{si}}\right) \tag{1}$$

and

$$\rho_L = q\left[N_d - N_a + p_o \exp\left(-\frac{\phi_L}{V_{th}}\right) - (n_o + \Delta n)\exp\left(\frac{\phi_L}{V_{th}}\right)\right], \tag{2}$$

where ϕ_L [V] is the potential at any point under illumination, ρ_L [C/cm^{-3}] is the charge density, N_d (N_a) [cm^{-3}] is the ionized donor (acceptor) density in the substrate, ϵ_o and ϵ_{si} [F/cm] is the dielectric constants of vacuum and silicon, respectively, and Δn [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

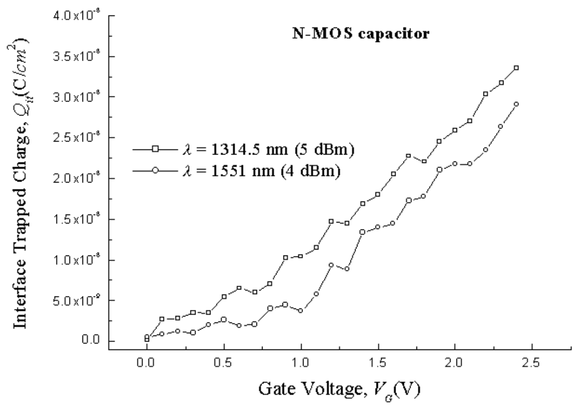

Fig. 2. Photoexcited interface trapped charge of an N-MOS capacitor.

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]:

$$Q_S = -\left(\frac{\sqrt{2V_{th}\epsilon_o\epsilon_{si}}}{L_D}\right)\left[V_{th}\exp\left(-\frac{\phi_{SL}}{V_{th}}\right) + \phi_{SL} - V_{th} + \frac{(n_{po}+\Delta n)}{p_{po}}\left(V_{th}\exp\left(\frac{\phi_{SL}}{V_{th}}\right) - \phi_{SL} - V_{th}\right)\right]^{1/2}, \tag{3}$$

where ϕ_{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 (ϕ_{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 λ = 1314.5 nm than with λ = 1551 nm because the photonic energy of λ = 1314.5 nm ($h\nu \cong$0.943 eV) is larger than that of λ = 1551 nm ($h\nu \cong$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 λ = 1551

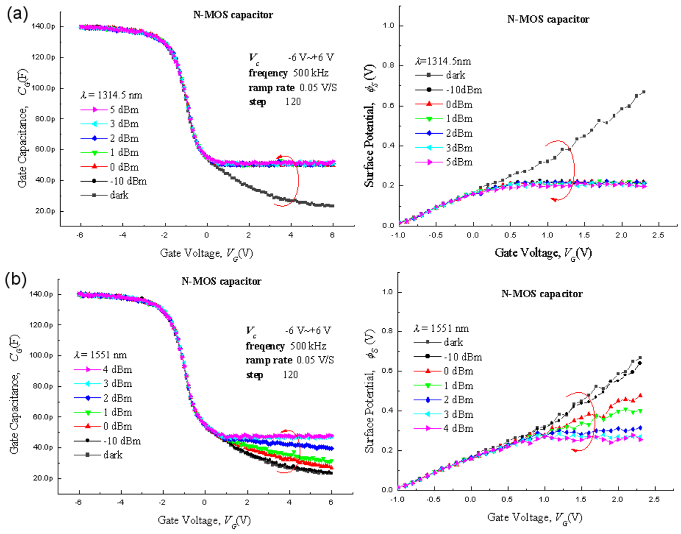

Fig. 3. Photonic response of N-MOS capacitors to various optical powers: (a) λ = 1314.5 nm and (b) λ = 1551 nm.

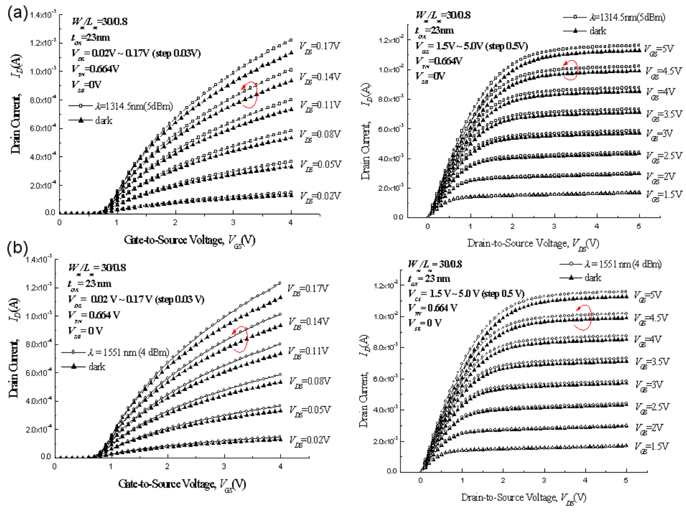

Fig. 4. Photonic $I_D - V_{GS}$, V_{DS} characteristic responses of an N-MOSFET: (a) λ = 1314.5 nm and (b) λ = 1551 nm.

nm depends strongly on the incident optical power.

Photoresponsive current-voltage characteristics ($I_D - V_{GS}$, V_{DS}) of n-channel MOSFETs with W/L = 30 μm/0.8 μm 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 $E_C - h\nu < E < E_C$ 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 (λ = 1314.5 nm, 1551 nm, $h\nu \sim 1.24/\lambda(\mu\text{m})$ eV) with energies less than the silicon band-gap energy ($h\nu < E_g$, E_g = 1.12 eV) were used in the photonic capacitance-voltage response of interface traps to a limited energy band ($E_C - h\nu < E < E_C$). Photonic capacitance-voltage characteristics of N- and P-MOS capacitors with W $\times$ L = 300 $\times$ 300 μm^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.

ACKNOWLEDGMENTS

This work was supported by KOSEF under the ERC program through the MINT research center at Dongguk University and in part by the BK21 Project.

REFERENCES

[1] E. Abou-Allam and T. Manku, IEEE CAD Integrated Circuit and Systems **16**, 437 (1997).

[2] M. Thamsirianunt and T. K. Kwasniewski, IEEE J. Solid-State Circ. **32**, 1511 (1997).
[3] K.-H. Baek, G. M. Lim, S. D. Cho, Y. C. Kim, H. C. Kim, S. K. Kim, D. J. Kim and D. M. Kim, J. Korean Phys. Soc. **36**, 915 (2000).
[4] M.-R. Lee and O.-K. Kwon, J. Korean Phys. Soc. **35**, Supp. 4, S586 (1999).
[5] S. Chang, S. Han, H. Shin and J. Lee, J. Korean Phys. Soc. **37**, 902 (2000).
[6] D. K. Schroder, *Semiconductor Material and Device Characterization* (Wiley, New York, 1990).
[7] P. Chakrabarti, B. R. Abraham, A. Dhingra, A. Das, B. S. Sharan and V. Maheshwari, IEEE Trans. Electron Devices **39**, 507 (1992).
[8] B. K. Mishra and P. Chakrabarti, Solid-State Electronics **38**, 255 (1995).
[9] H. J. Kim, D. M. Kim, D. H. Woo, S.-I. Kim, S. H. Kim, J. I. Lee, K. N. Kang and K. Cho, Appl. Phys. Lett. **72**, 584 (1998).
[10] D. M. Kim, H, J, Kim, J. I. Lee and Y. J. Lee, IEEE Trans. Electron Device Lett. **21**, 264 (2000).
[11] N. Arora, *MOSFET Models for VLSI Circuit Simulation Theory and Practice* (Springer-Verlag, New York, 1993).
[12] S. Wolf, *Silicon Processing for the VLSI Era: Volume 3-The Submicron MOSFET* (Lattice Press, New York, 1995).
[13] D. A. Neamen, *Semiconductor Physics and Devices* (Irwin, New York, 1992).