Fig. 3(c) and (d) depicts the drain current noise as a function of the drain current and the zero voltage drain–source conductance for a short channel device at 2.5 GHz for V_{ds} of 1, 2, and 3 V. The drain noise for modest biases follows the classical shot noise equation $(2qI_{ds})$. This strongly correlates with a high diffusion current density component in the short channel MOSFET [Fig. 2(b)]. Although the duffusion current density accounts for only a fraction of the channel current density, the noise contribution is dominant. The best operating point [11]–[13] for noise occurs in the region where shot noise is predominant. Note also that a saturation of the noise at higher I_{ds} values is due to almost constant diffusion current contribution to the total drain current discussed above.

From Fig. 3(d), we can see that there is no obvious relationship between drain noise and g_{do}. There are a number of empirical equations relating g_{do} and I_{ds} to the drain current noise, but most of these relationships have many fitting parameters and are not physically based.

VI. Conclusions

Diffusion-drift based 2-D noise simulation agrees well with experimental data for submicron MOSFETs. Hot electron contribution to noise is not significant for 0.5 μm gate MOSFETs. High excess noise is due to the shot noise caused by diffusion of carriers in the channel.

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Photonic High-Frequency Capacitance–Voltage Characterization of Interface States in Metal-Oxide-Semiconductor Capacitors

D. M. Kim, H. C. Kim, and H. T. Kim

***Abstract*—A new characterization method based on the photonic high-frequency capacitance–voltage (HF C–V) response of metal-oxide semiconductor (MOS) capacitors is reported for the analysis of interface states in MOS systems. An optical source with a photon energy less than the silicon band-gap ($h\nu = 0.799$ eV $< E_g = 1.11$ eV) is employed for the photonic characterization of interface states ($E_{\rm it}$) distributed in the photoresponsive energy band ($E_C - h\nu < E_{\rm it} < E_C$) in N-MOS capacitors with a polysilicon gate. Assuming a uniform distribution of the trap levels, the density of interface states ($D_{\rm it}$) was observed to be $D_{\rm it} =$ 1–5 $\times 10^{11}$ eV^{-1}cm^{-2} in the photoresponsive energy band.**

***Index Terms*—Capacitance–voltage (C–V), interface states, MOS capacitor, photonic characterization, traps.**

I. Introduction

Interface states at the SiO_2/Si heterojunction in metal-oxide semiconductor (MOS) structures play a crucial role in determining the threshold voltage (V_T), channel carrier mobility (μ), transconductance (g_m), and other electrical characteristics of metal-oxide semiconductor field-effect transistors (MOSFETs) [1], [2]. Accurate characterization of interface states throughout the band-gap is, therefore, one of the most important topics for improving the robustness of devices and their integrated circuits with MOS capacitors and MOSFETs. Besides the charge-pumping method by Groeseneken et al. [3] and the deep level transient spectroscopy (DLTS) by Lang [4], there have been enormous efforts on the characterization of interface traps in MOS capacitors and MOSFETs [2], [5], [6]. There have also been extensive works on the characterization and/or applications of photonic effects on MOS capacitors and MOSFETs with photon energy $(h\nu)$ greater than the energy band gap (E_g) [7]–[10].

In this paper, we propose a new nondestructive photonic high-frequency capacitance–voltage (HF C–V) method for the characterization of interface states in MOS capacitors and MOSFETs that combines photonic high-frequency capacitance–voltage characteristics with the photon energy less than the silicon band-gap energy. Distribution and density ($D_{\rm it}$ [eV^{-1}cm^{-2}]) of trap levels ($E_{\rm it}$ [eV]) in the photo-responsive energy band at the SiO_2/Si heterojunction in the MOS structures are experimentally investigated by the photonic HF C–V method.

II. Photonic HF C–V Characterization of Interface States

High-frequency capacitance–voltage (C–V) characteristics of MOS capacitors (fabricated by a standard CMOS process with an n$^+$ polysilicon gate; $t_g \sim 300$ nm, $t_{\rm ox} = 23$ nm, $N_A = 2 \times 10^{16}$ cm^{-3}) were investigated under optical illumination. In order to suppress a band-to-band excitation from the silicon substrate and stimulate the photo-excitation of excess carriers from the SiO_2/Si interface states

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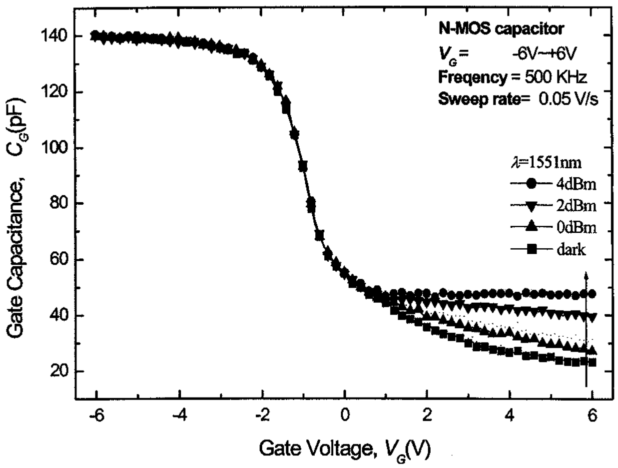

Fig. 1. Photonic high-frequency C–V characteristics of an N-MOS capacitor with a polysilicon gate under optical input ($\lambda = 1551$ nm and $h\nu = 0.799$ eV) ($P_{\rm opt} =$ ●: 4 dBm, ▼: 2 dBm, ▲: 0 dBm, ■: dark).

(NMOS; $E_V < E_C - h\nu < E_{\rm it} < E_C$), an optical source with a photon energy ($h\nu = 0.799$ eV) less than the silicon band-gap energy ($E_g = 1.11$ eV) was chosen. Characterization of MOS capacitors was performed on a wafer with an optical input ($\lambda = 1551$ nm, $P_{\rm opt,max} = 4$ dBm) via a cleaved multimode optical fiber (illumination diameter ~200 μm) and a precision LCR meter HP4284A. We note that there was no antireflection coating on the surface of MOS capacitors. Even though polysilicon gate is transparent to the optical illumination, the optical power delivered to the device under test could be slightly different from $P_{\rm opt}$. Photonic HF C–V characteristics of N-MOS capacitors with $W \times L = 300 \times 300\ \mu{\rm m}^2$ were measured. In order to minimize the unnecessary response of interface states caused by the measurement signal (small ac signal and DC sweep voltage) and observe a change in the photonic HF C–V curve caused only *by optically excited interface states*, we kept the small-signal frequency high ($f = 500$ kHz) and the sweep rate fast ($S = 50$ mV/s) for a deep-depletion mode operation without optical input as well as employing the photon energy $h\nu < E_g$.

Measured photonic HF C–V characteristics of an N-MOS capacitor are shown in Fig. 1. The high-frequency capacitance is significantly modulated by the photo-excited carriers. Due to a fast DC sweep rate and a high frequency small signal, the HF C–V curve without an optical input shows a deep-depletion C–V characteristics. With an increasing $P_{\rm opt}$, on the other hand, the photonic C–V characteristics gradually converge to a typical HF C–V curve due to the contribution of photo-generated excess channel carriers from the interface states at SiO_2/Si hetero-interface. This is strong evidence that the photoresponsive variation in the HF C–V characteristics under illumination is due to photo-excited carriers from the interface states because we employed an optical source with $h\nu < E_g$ and therefore, the photonic generation is expected only from the interface traps in the photoresponsive energy band $(E_V < E_C - h\nu < E_{\rm it} < E_C)$ for N-MOS capacitors.

Gate-bias dependent HF C–V characteristics of MOS capacitors under optical illumination have been also investigated. Under the accumulation mode $(V_G < 0)$, due to a relatively small density of excess carriers $(\Delta n_{\rm it} \ll N_A)$ excited from interface states, no significant change in the photonic HF C–V characteristics were observed. The variation in the photonic HF C–V characteristics in the strong inversion $(V_G > V_{\rm TN})$, on the other hand, was very sensitive to the optical input predominantly caused by the measurable amount of excess carriers from the interface states at the SiO_2/Si interface (trapped electrons) compared with the electrically induced quasi-steady state inversion charges.

The charge density under the gate in N-MOS capacitors can be obtained from the Poisson's equation and charge distribution $\rho_L(x)$ through [11]

$$\nabla^2 \phi_L(x) = -\frac{\rho_L(x)}{\varepsilon_{\rm si}} \tag{1}$$

$$\rho_L(x) = -q\left[N_a(x) - N_d(x) - p_{\rm po}e^{-\phi_L(x)/V_{\rm th}} + n_{\rm po}e^{\phi_L(x)/V_{\rm th}}\right] \tag{2}$$

where $V_{\rm th} = kT/q$; the thermal voltage $\phi_L(x)$ [V]; the potential at any point under illumination $N_a(N_d)$ [cm^{-3}]; an ionized acceptor(donor) density in the substrate $\varepsilon_{\rm si}$ [F/cm]; the dielectric constant of Si, and $n_{\rm po}(p_{\rm no})$; electron (hole) concentration in the substrate area under thermal equilibrium. At a large positive gate voltage in N-MOS, capacitors with a uniform acceptor doping (N_A), the negative surface charge density per unit area; Q_S [C/cm^2] (a combination of the depleted acceptor charge Q_d, the inverted free electron charge Q_i, and the interface charge $Q_{\rm it}$) as a function of the surface potential $(\phi_{\rm SL})$ in the semiconductor at the SiO_2/Si heterojunction interface can be simply obtained from [11], [12]

$$Q_S \cong -\sqrt{2q\varepsilon_{\rm si}N_A V_{\rm th}\left(\frac{\phi_{\rm SL}}{V_{\rm th}} + \frac{n_{\rm po}}{p_{\rm po}}\exp\left(\frac{\phi_{\rm SL}}{V_{\rm th}}\right)\right)}. \tag{3}$$

Excess carriers $(\Delta n = n - n_{\rm po} = \Delta n_e + \Delta n_{\rm opt})$ are modulated by optical illumination $(\Delta n_{\rm opt})$ as well as by the gate voltage (Δn_e). The increased surface charge density by the photogeneration from the interface states $(\Delta n_{\rm opt} = \Delta n_{\rm it})$ in the photoresponsive energy band results in the variation of the surface potential over the modulation by V_G. The gate capacitance $(C_G = dQ_s/dV_G)$ is modulated by photoexcited electrons from the interface states in addition to the modulation by V_G through a variation of $\phi_{\rm SL}$ during the photonic HF C–V characterization. Therefore, the surface potential under depletion approximation can be experimentally obtained from the measured photonic HF C–V characteristics as a function of $V_{\rm GS}$ and described by

$$\phi_{\rm SL} = \left(\frac{\varepsilon_{\rm si}qN_A}{2}\right)\left(\frac{C_{\rm ox} - C_G}{C_{\rm ox}C_G}\right)^2 \tag{4}$$

where $C_{\rm ox} = \varepsilon_{\rm ox}/t_{\rm ox}$ is the fixed-oxide capacitance and C_G is the V_G- and $P_{\rm opt}$-dependent total gate capacitance per unit area obtained from the photonic HF C–V measurement.

Combining the experimental HF C–V data with analytical results as a function of $P_{\rm opt}$ and V_G, the surface potential at the Si/SiO_2 heterojunction interface was obtained and plotted in Fig. 2. Photoexcited excess carries from the interface states induce a decreased surface potential $(\phi_{\rm SL})$ under a constant gate voltage as shown in Fig. 2. In the deep depletion mode without optical illumination, the variation of the surface charge is mainly caused by the depleted acceptor charges. However, a change in the surface charge under a fast sweep rate with optical illumination can be replaced in part by the photogenerated excess electrons from the interface states below the quasi-Fermi level. Due to the build-up of photoexcited excess electrons at the SiO_2/Si hetero-interface, which is known as *the photovoltaic effect*, the reduced surface potential results in the compression of the depletion width and increase in the capacitance. Considering the magnitude of the photon energy $h\nu < E_g$, these excess carriers are expected to be generated from the trap levels located only in the photoresponsive energy band $E_C - h\nu < E_{\rm it} < E_C$. Assuming that the modulation of photonic HF C–V characteristics are caused by the photoexcitation of interface

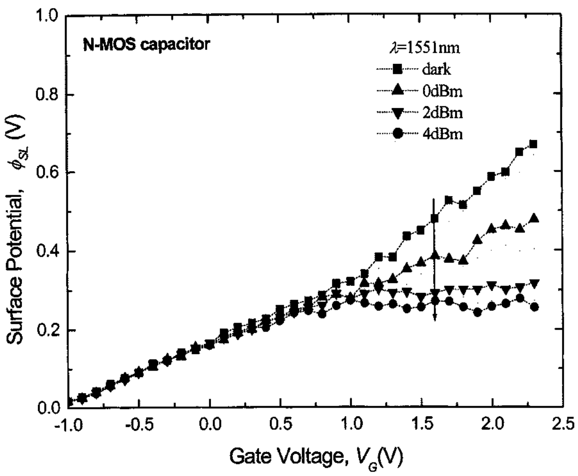

Fig. 2. Surface potential $\phi_{\rm SL}$ of an N-MOS capacitor as a function of the gate bias under optical illumination ($P_{\rm opt}$ = •: 4 dBm, ▼: 2 dBm, ▲: 0 dBm, ■: dark).

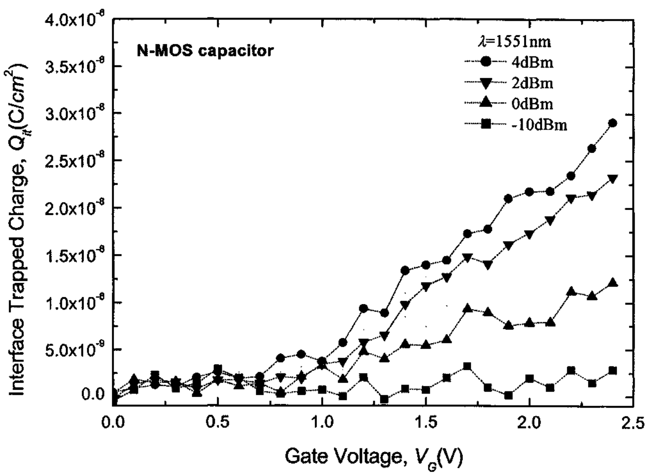

Fig. 3. Interface trapped charge density $Q_{\rm it}$ as a function of the optical power for a specific gate bias. ($P_{\rm opt}$ = •: 4 dBm, ▼: 2 dBm, ▲:0 dBm, and ■: -10 dBm).

states, we conclude that the capacitance of MOS capacitors increases solely due to the generation of excess carriers from the interface states under optical illumination.

Based on the experimental surface potential extracted from the photonic HF C–V characteristics, the interface charge density ($Q_{\rm it}$ C/cm^2) at the SiO_2/Si interface can be obtained by the difference between Q_S and $Q_{\rm So}$ and described by $Q_{\rm it} \equiv Q_S(P_{\rm opt}) - Q_{\rm So}$ in which Q_S and $Q_{\rm So}$ correspond to the surface charge densities with and without photo-excitation, respectively. Using the two-dimensional (2-D) charge density equation and HF C–V data, the density of the photogenerated interface charge ($Q_{\rm it} = 5 \times 10^{-9}$–$4 \times 10^{-8}$ C/cm^2) at SiO_2/Si heterointerface has been plotted in Fig. 3 as a function of $P_{\rm opt}$ for a specific V_G. Assuming a uniform distribution of interface states in the photoresponsive energy band $(E_C - h\nu < E_{\rm it} < E_C)$, the 2-D density $(\Delta n_{\rm it})$ of the photo-generated interface states can be obtained from

$$\Delta n_{\rm it} = \int_{E_C - h\nu}^{E_C} D_{\rm it}(E)\, dE = Q_{\rm it}/q. \tag{5}$$

It was observed to be $\Delta n_{\rm it} = 1$–4×10^{11} cm^{-2} for the N-MOS capacitor. Under the assumption of a uniform distribution, the average density of interface states per unit energy $\tilde{D}_{\rm it}$ [eV^{-1}cm^{-2}] can be obtained from

$$\tilde{D}_{\rm it} \equiv \Delta n_{\rm it}/\Delta E = \Delta n_{\rm it}/h\nu \tag{6}$$

and it was extracted to be $D_{\rm it} = 1$–5×10^{11} eV^{-1}cm^{-2} throughout the photoresponsive energy band.

III. Conclusion

The density and distribution of interface traps were investigated using the photonic high-frequency C–V characteristics of MOS capacitors. An optical source with a photon energy less than the silicon band-gap energy is employed for the characterization of interface states distributed over the photoresponsive energy band $(E_C - h\nu < E_{\rm it} < E_C)$. From the photonic HF C–V characterization method applied to N-MOS capacitors with a polysilicon gate, the density and the average density of interface states in the photoresponsive energy band were observed to be $\Delta n_{\rm it} = 1$–4×10^{11} cm^{-2} and $D_{\rm it} = 1$–5×10^{11} eV^{-1}cm^{-2}, respectively. We also expect that a comprehensive characterization of interface states over the energy bandgap $(E_V < E_{\rm it} < E_C)$ can be obtained from the photonic HF C–V method using a wavelength-modulated optical input with $0 < h\nu < E_g$.

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