Subbandgap Optical Differential Body-Factor Technique and Characterization of Interface States in SOI MOSFETs

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***Abstract*—A distribution of interface states ($D_{\rm it}$) in SOI MOSFETs has been characterized by a subbandgap optical differential body-factor (SODBoF) technique. We adopted a subbandgap ($E_{\rm ph} < E_g$) optical source as a virtual gate on the body-contactless SOI MOSFETs under the subthreshold ($V_{\rm GS} < V_T$) current–voltage characteristics. Employing a differentiation to the body factor, any possible error from the threshold voltage is also suppressed. We applied the SODBoF technique to n- and p-channel SOI MOSFETs on the same wafer and verified the result. Extracted traps over the bandgap ranges $D_{\rm it} = 10^{10}–10^{11}$ cm$^{-2} \cdot$ eV^{-1} with a typical U-shape.**

***Index Terms*—Differential body factor, interface states, silicon on insulator (SOI), subbandgap optical illumination, subthreshold slope.**

I. Introduction

In THE development of metal–oxide-semiconductor field-effect transistors (MOSFETs) on silicon-on-insulator (SOI) wafers [1], the energy distribution of interface states ($D_{\rm it}$) over the bandgap ($E_V < E_t < E_C$) is one of the most important parameters to be characterized for robust design and implementation of integrated circuits and systems [2]–[4]. There are conventional techniques such as electrical charge pumping [5], [6] and subthreshold current method [7], [8]. However, there is a difficulty in the characterization of interface states in SOI MOSFETs, due to a structural absence of the body contact. They also require complicated measurement procedure and are sensitive to external factors.

In this letter, we propose and experimentally verify the subbandgap optical differential body-factor (SODBoF) technique for a simple and robust characterization of interface states over the bandgap energy in SOI MOSFETs. The proposed technique is based on the modulation of the body factor under a subbandgap optical illumination. With the subbandgap photon energy ($E_{\rm ph} = h\boldsymbol{v} < E_g$), a change in the body factor is observed due to optically generated excess carriers excited from the interface states, while electron–hole pair generation through band-to-band generation is suppressed [9]. Employing a differential change of the body factor as a function of the gate voltage, which is mapped to the energy level, the energy distribution of interface states is extracted without any possible error coming from the threshold voltage which is very sensitive to the extraction method.

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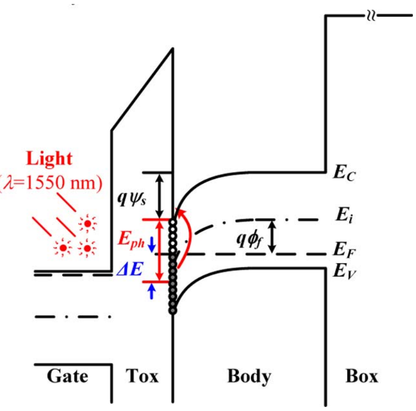

Fig. 1. Energy band diagrams under subbandgap ($E_{\rm ph} < E_{g,{\rm Si}}$) optical illumination in n-channel SOI MOSFETs. The trapped electrons within the photoresponsive energy ($E_C - E_{\rm ph}) < E_t < (E_i - q\varphi_f \pm q\psi_s$) are excited to the conduction band and contribute to the drain current.

II. SODBoF Technique for Extraction of Traps

An optical source for the SODBoF technique is chosen to have a subbandgap photon energy ($E_{\rm ph} = 0.81$ eV $< E_{g,{\rm Si}} =$ 1.1 eV) through regulating the wavelength (λ or frequency $\boldsymbol{v}$). This pumps up only trapped charges at the interface states in a limited photoresponsive range over the bandgap energy [10].

Schematic energy band diagrams of SOI MOSFETs with subbandgap photons are comparatively shown in Fig. 1. Here, the substrate doping (N_A)-dependent Fermi level is indicated as E_F and $q\varphi_f$. The amount of trapped electrons contributing to the drain current is related to the photoresponsive range $\Delta E (= E_F - (E_C - E_{\rm ph}))$ at the $\rm SiO_2/Si$ interface. It is the energy range corresponding to the gate voltage ($V_{\rm GS} = V_{\rm FB} + \psi_{\rm ox} + \psi_s$) or/and photon energy ($E_{\rm ph}$) as a function of the surface potential (ψ_s). At the threshold voltage condition ($0 < V_{\rm GS} < V_T$), as shown in Fig. 1, the photoresponsive

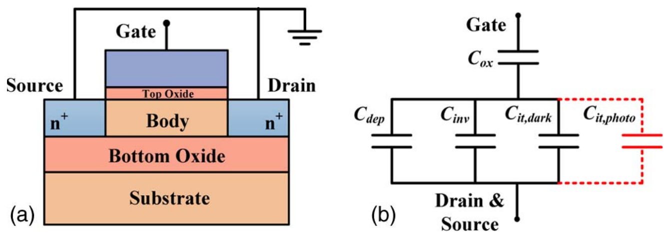

Fig. 2. (a) SOI MOSFET structure and (b) its equivalent capacitive circuit model with a subbandgap optical illumination for SODBoF technique. $C_{\text{it,photo}}$ is the capacitive component originated from the photoexcited carriers from the photoresponsive traps.

energy is modulated into $(E_C - E_{\text{ph}}) < E_t < (E_i - q\varphi_f)$ in n-MOSFETs. Therefore, the photoresponsive energy under subbandgap optical illumination is obtained to be $(E_c - E_{\text{ph}}) < E_t < (E_i - q\varphi_f \pm q\psi_s)$ in n-MOSFETs.

A three-terminal SOI MOSFET structures and its equivalent capacitance model are shown in Fig. 2. The top oxide capacitance (C_{ox}) is in a series with the depletion capacitance (C_{dep}) and in parallel with the interface capacitance (C_{it}). The capacitance for the buried oxide layer (C_{box}) and inversion charge capacitance (C_{inv}) can be neglected, due to its considerable thickness ($T_{\text{box}} = 375$ nm) and small amount of the inversion charges (Q_{inv}) compared with the depletion charge (Q_{dep}) in depletion region, particularly under subthreshold bias condition, ($V_{\text{GS}} < V_T$). We note that the interface capacitance (C_{it}) is decomposed into $C_{\text{it,photo}}$ and $C_{\text{it,dark}}$ which are modulated by the gate bias under optical illumination. Photoresponsive interface capacitance ($C_{\text{it,photo}}$) is coming from the subbandgap photoexcited carriers from traps over the photoresponsive energy in SOI MOSFETs.

Considering the photovoltaic effect on the threshold voltage of SOI MOSFETs under optical illumination, the subthreshold ($V_{\text{GS}} < V_T$, $V_{\text{DS}} > 3V_{\text{th}}$) drain current under dark and subbandgap optical illumination can be written as [11]

$$I_D \cong I_{Do} \exp\left(\frac{V_{\text{GS}} - V_{\text{TN}}}{m(V_{\text{GS}})V_{\text{th}}}\right) \tag{1}$$

where $V_{\text{th}}(= kT/q)$ is the thermal voltage, V_{TN} is the threshold voltage in n-type MOSFETs, I_{Do} is the drain current at the threshold ($V_{\text{GS}} = V_T$), and m is the body factor that indicates the gate voltage coupling degree to the surface. Thus, V_{GS}-dependent body factors $m_{\text{dark}}(V_{\text{GS}})$ and $m_{\text{photo}}(V_{\text{GS}})$ are described by

$$m_{\text{dark}}(V_{\text{GS}}) = 1 + \frac{C_{\text{dep}}(V_{\text{GS}}) + C_{\text{it,dark}}(V_{\text{GS}})}{C_{\text{ox}}} \tag{2}$$

$$m_{\text{photo}}(V_{\text{GS}}) = m_{\text{dark}}(V_{\text{GS}}) + \frac{C_{\text{it,photo}}(V_{\text{GS}})}{C_{\text{ox}}}. \tag{3}$$

We note that C_{ox} and C_{dep} can be experimentally obtained from C–V characteristics of the MOS systems or process information of the oxide thickness and substrate doping concentration.

The surface potential $\psi_S(V_{\text{GS}})$ to map the gate voltage into the trap energy level E_t is obtained through

$$\psi_s(V_{\text{GS}}) = \left(\sqrt{\frac{2qN_A\varepsilon_{\text{Si}}}{4C_{\text{ox}}^2} + (V_{\text{GS}} - V_{\text{FB}})} - \frac{\sqrt{2qN_A\varepsilon_{\text{Si}}}}{2C_{\text{ox}}}\right)^2. \tag{4}$$

Therefore, body factors under dark and subbandgap optical illumination can be derived from the measured subthreshold current as

$$m(V_{\text{GS}}) \cong \left(\frac{V_{\text{GS}} - V_{\text{TN}}}{V_{\text{th}}}\right) \Big/ \ln\left(\frac{I_D(V_{\text{GS}})}{I_{Do}}\right). \tag{5}$$

We also note that, in the SODBoF technique, the subbandgap photons generate excess carriers only from the interface states and there is no excess carrier generation either from the gate oxide or from the Si substrate through the band-to-band generation. This means that the difference between $I_{D,\text{dark}}$ and $I_{D,\text{photo}}$ comes only from the photoinduced variation of $C_{\text{it,photo}}$ (V_{GS}) and $m_{\text{photo}}(V_{\text{GS}})$. Therefore, $C_{\text{it,photo}}(V_{\text{GS}})$ related to the density of interface states can be obtained from the difference between $m_{\text{dark}}(V_{\text{GS}})$ and $m_{\text{photo}}(V_{\text{GS}})$ through (2)–(5) as

$$m_{\text{photo}}(V_{\text{GS}}) - m_{\text{dark}}(V_{\text{GS}}) = \frac{C_{\text{it,photo}}(V_{\text{GS}})}{C_{\text{ox}}}. \tag{6}$$

However, as expected from (5), each body factor is quite sensitive to the threshold voltage, so it may result in a significant error in the interface states depending on the threshold voltage extraction method. Therefore, a differentiation is applied to the body factors in order to eliminate the effect of the threshold voltage, and we obtain

$$m(V_{\text{GS}}) = \left(\frac{(V_{\text{GS}} + \Delta V_{\text{GS}}) - V_{\text{GS}}}{V_{\text{th}}}\right) \Big/ \ln\left(\frac{I_D(V_{\text{GS}} + \Delta V_{\text{GS}})}{I_{Do}}\right) \tag{7}$$

with ΔV_{GS} as the step for the gate voltage sweep during the I-V characterization.

The trap density at the Si/SiO_2 interface can be obtained by combining (6) with (7), and we obtain

$$\frac{dC_{\text{it}}(\psi_s)}{d\psi_s} = C_{\text{ox}}\left(\frac{dm_{\text{photo}}(V_{\text{GS}})}{dV_{\text{GS}}} - \frac{dm_{\text{dark}}(V_{\text{GS}})}{dV_{\text{GS}}}\right) \Big/ \left(\frac{d\psi_s}{dV_{\text{GS}}}\right). \tag{8}$$

Through the proposed SODBoF technique, we finally obtain the energy distribution of D_{it} over the photoresponsive energy in the bandgap through

$$\begin{aligned} D_{\text{it}}(\psi_S) &= \frac{\Delta C_{\text{it}}(\psi_s)}{q^2} \\ &= \frac{C_{\text{ox}}}{q^2}\left[\left(\frac{dm_{\text{photo}}(V_{\text{GS}})}{dV_{\text{GS}}} \right.\right. \\ &\qquad \left.\left. - \frac{dm_{\text{dark}}(V_{\text{GS}})}{dV_{\text{GS}}}\right) \Big/ \left(\frac{d\psi_s}{dV_{\text{GS}}}\right)\right] \Delta\psi_s. \end{aligned} \tag{9}$$

III. Experimental Result and Discussion

We applied the proposed SODBoF technique to n- and p-type SOI MOSFETs fabricated by a standard CMOS process with n^+ and p^+ poly silicon gates. The gate oxide thickness is confirmed to be 20 nm through SEM, and the silicon body doping concentration is known to be $N_A = 3 \times 10^{17}$ cm^{-3} for n-MOSFETs and $N_D = 3 \times 10^{17}$ cm^{-3} for p-MOSFETs. I_D–V_{GS} characteristics of n-channel SOI MOSFET ($W/L = 2$ μm/2 μm, the thickness of the top/buried oxide = 20 nm/

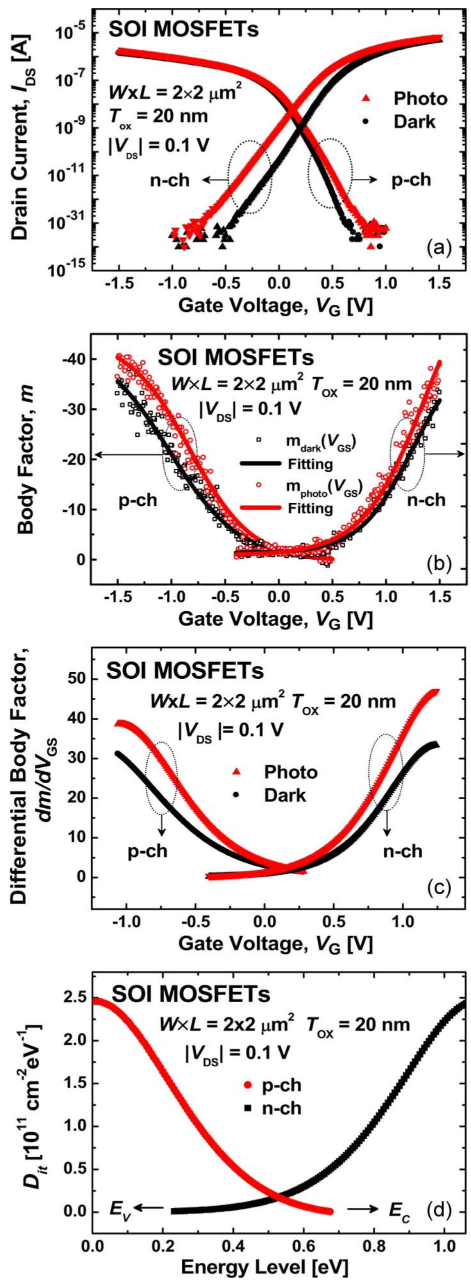

Fig. 3. (a) $I_D - V_{\rm GS}$ characteristics of SOI MOSFETs with $W/L = 2\ \mu\text{m}/2\ \mu\text{m}$ and $t_{\rm ox} = 20$ nm under subbandgap optical illumination and dark. (b) Body factor (experimental and fitted curve). (c) Differential body factors $dm_{\rm photo}/dV_{\rm GS}$ and $dm_{\rm dark}/dV_{\rm GS}$ are obtained from subthreshold slope, and (d) energy distribution of $D_{\rm it}$ over the bandgap ranges is obtained through the SODBoF technique.

375 nm, respectively) were characterized by a semiconductor parameter analyzer (Agilent 4156C) combined with optical source (ILX Lightwave Corporation, Model 7200, $\lambda = 1550$ nm, $E_{\rm ph} = 0.81$ eV, and $P_{\rm opt} = 1.36$ mW). Optical illumination is delivered well into the device through an optical fiber with a diameter $d = 50\ \mu$m which fully covers the device under characterization. Since the gate is poly-Si having a transparent property, the subbandgap photons reach the $\mathrm{SiO_2/Si}$ interface without absorption during the delivery to the interface.

For SOI MOSFETs, due to a photovoltaic and photoconductive effect, V_T shift and SSW degradation are observed under a subbandgap optical illumination in comparison with dark states shown in Fig. 3(a). Due to photoexcited excess carriers from traps over the photoresponsive energy, the drain current increases in the subthrehold region. We also note that the interface state capacitance $(C_{\rm it})$ induced by the excess carriers from the photoresponsive traps degrades the subthreshold slope due to suppressed controllability of the gate voltage to the substrate potential. The gate voltage-dependent body factors $m_{\rm photo}(V_{\rm GS})$ and $m_{\rm dark}(V_{\rm GS})$ obtained from subthreshold slope of transfer curves are shown in Fig. 3(b). Due to a fluctuation caused by the differentiation of the discrete measurement data, fitting is used for smoothing. Moreover, $V_{\rm GS}$-dependent differential body factors $dm_{\rm photo}(V_{\rm GS})/dV_{\rm GS}$ and $dm_{\rm dark}(V_{\rm GS})/dV_{\rm GS}$ are comparatively shown in Fig. 3(c). Apparent changes dependent on the gate bias are confirmed. The interface trap density ranges $D_{\rm it} = 10^{10}–10^{11}\ \text{cm}^{-2}\ \text{eV}^{-1}$ with a U-shaped distribution over the bandgaps shown in Fig. 3(d).

IV. Conclusion

We have proposed a SODBoF technique for extraction of interface states $D_{\rm it}$ over the energy bandgap in body-contactless SOI MOSFETs. By employing a differential body factor in the subthreshold region, V_T-insensitive characterization of SOI MOSFETs without a body contact is achieved. The SODBoF technique was successfully applied to n- and p-channel SOI MOSFETs and obtained the density of interface states $D_{\rm it} = 10^{10}–10^{11}\ \text{cm}^{-2} \cdot \text{eV}^{-1}$ over the bandgap.

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