Interface-Trap Analysis by an Optically Assisted Charge-Pumping Technique in a Floating-Body Device

Sungho Kim, Sung-Jin Choi, and Yang-Kyu Choi

***Abstract*—An optically assisted charge-pumping (CP) technique is proposed for the characterization of interface traps in floating-body (FB) devices. Even without a body contact, majority carriers can be supplied into the FB by light illumination, which contributes to enabling the CP process. Under a strong inversion enabled by a back gate, the front gate triggers the CP process with a designed pulse waveform. Consequently, modulation of the majority-carrier concentration at the front interface is monitored by the change of the drain current. Thus, the interface-trap density is extracted from the monitored drain current and the developed analytical model.**

***Index Terms*—Charge pumping, floating-body (FB), interface trap, silicon-on-insulator MOS field-effect transistor (FET).**

I. Introduction

THE POTENTIAL use of floating-body (FB) devices as parts in upcoming devices has attracted considerable attention from various research areas, including those related to nanowire- or nanobelt-based field-effect transistors (FETs). When a device is scaled down to the nanometer scale, however, characterization of the interface-trap density becomes a serious concern for advanced applications that utilize FB devices due to the increased surface-to-volume ratio. Consequently, the electrical properties of FB devices are strongly influenced by the interface-trap state. Occasionally, the trap state was intentionally utilized for photodetectors [1]. On the other hand, the effect of trap state has been both considered [2] and, more commonly, ignored [3]–[5].

To analyze interface-trap states electrically, a charge-pumping (CP) technique is widely used [6], [7]. Unfortunately, the conventional CP technique is not directly applicable to FB devices unless an extra body contact is formed because the supply of majority carriers to the body is indispensable for the CP process. Thus far, specially designed device structures, which include an extra body contact [8] or gated-diode-like devices [9], instead have been used for CP measurements in FB devices. However, these types of approaches require additional fabrication processes that are associated with several geometric problems. In this letter, a unique optically assisted CP technique and its analytical model are demonstrated for the characterization of the interface-trap state in FB devices. This optically assisted CP technique (henceforth termed simply as optical CP) can be adapted in both partially and fully depleted FB devices without structural modifications. Simple measurements with proper extraction procedures reliably provide the interface-trap density in FB devices.

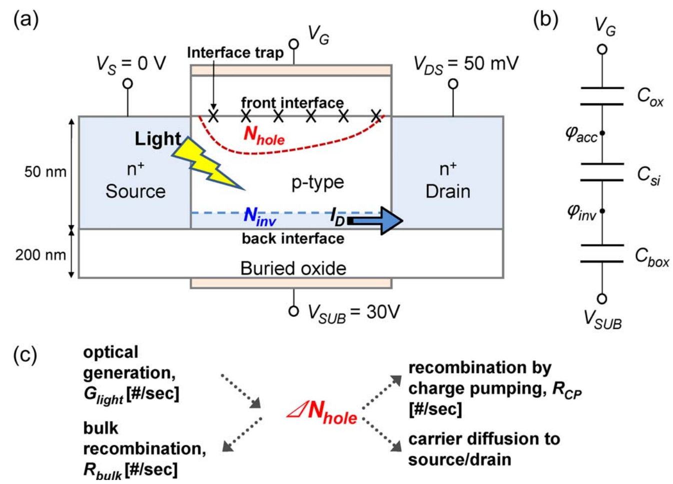

Fig. 1. (a) Cross-sectional view of the fabricated device and the measurement setup. (b) Equivalent circuit to model the fully depleted n-channel FB FET. (c) Four different factors to determine the modulation of the hole density.

II. Results and Discussion

The proposed optical CP was applied to a fully depleted silicon-on-insulator n-channel FET whose channel length, channel width, and gate dielectric (SiO_2) thickness were 2 μm, 5 μm, and 5 nm, respectively. A top-silicon thickness of 50 nm was doped by boron at a concentration of 7×10^{15} cm^{-3}, and n^+ polycrystalline silicon was used as a gate. An intensity of 100 mW/cm^2 from a halogen lamp was used as a light source. The light intensity and wavelength spectrum are not critical parameters in optical CP measurements. A cross-sectional view of the fabricated device is schematically shown in Fig. 1(a). During the optical CP measurements, the back gate

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was sustained with a positive voltage V_{SUB} so as to induce an inversion layer at the back interface. A constant drain voltage (V_{DS}) was applied, and the drain current (I_D) transients were then monitored. Additionally, the front gate was biased with a designed pulse waveform for the CP process. The biasing level and timing condition of the front-gate voltage (V_G) are discussed later in this letter.

In this process, modulation of the hole density at the front interface owing to the light illumination and CP process is monitored via the transient drain-current characteristics. Therefore, first, both the transient behavior of the electron density (N_{inv}) at the back interface according to the hole density (N_{hole}) at the front interface and the electric field (E) in the body are analytically modeled under constant values of V_G and V_{SUB}, as shown in Fig. 1(b). In this configuration, the potential of the back interface (φ_{inv}) is approximated to be constant because the inversion layer is electrically connected to the n$^+$ source/drain (S/D) regions. On the other hand, the front interface is left floating because the accumulated holes at the front interface are separated from the n$^+$ regions of S/D by diffusion barriers at p-n junctions. The potential of the front interface (φ_{acc}) is determined by N_{hole} and V_G. The change of the potential φ_{acc} is given by $(C_{\mathrm{ox}} + C_{\mathrm{si}}) \cdot \Delta\varphi_{\mathrm{acc}} = q \cdot \Delta N_{\mathrm{hole}}$, where C_{si} and C_{ox} are the capacitance values of the FB and the gate oxide, respectively. A change of φ_{acc} leads to a change of the electric field in the FB according to $\varepsilon_{\mathrm{si}} \cdot \Delta E = -C_{\mathrm{si}} \cdot \Delta\varphi_{\mathrm{acc}}$, where $\varepsilon_{\mathrm{si}}$ is the permittivity of silicon. Given that the electric field in the buried oxide is kept constant, the inversion electron density changes according to $-q \cdot \Delta N_{\mathrm{inv}} = \varepsilon_{\mathrm{si}} \cdot \Delta E$. Accordingly, ΔN_{hole} is associated with ΔN_{inv} as $\Delta N_{\mathrm{hole}} = (1 + C_{\mathrm{ox}}/C_{\mathrm{si}}) \cdot \Delta N_{\mathrm{inv}}$. In addition, N_{inv} determines I_D as $N_{\mathrm{inv,light}} = N_{\mathrm{inv,dark}} \cdot (I_{D,\mathrm{light}}/I_{D,\mathrm{dark}})$, where $I_{D,\mathrm{dark}}$ is the measured value of I_D in a dark condition and $I_{D,\mathrm{light}}$ is the measured value of I_D when the hole accumulates upon light illumination. Here, ΔN_{inv} is $N_{\mathrm{inv,light}} - N_{\mathrm{inv,dark}}$, and $N_{\mathrm{inv,dark}}$ is $(A_G C_{\mathrm{box}}/q)(V_{\mathrm{SUB}} - V_{\mathrm{th}})$, where A_G is the device area, C_{box} is the capacitance of the buried oxide, and V_{th} is the threshold voltage of the back interface in thermal equilibrium at a negative V_G. Consequently, the relationship between ΔN_{hole} due to hole accumulation and the measured value of the change of I_D is given as $\Delta N_{\mathrm{hole}} = (1 + C_{\mathrm{ox}}/C_{\mathrm{si}})(A_G C_{\mathrm{box}}/q)(V_{\mathrm{SUB}} - V_{\mathrm{th}})(I_{D,\mathrm{light}}/I_{D,\mathrm{dark}} - 1)$.

Here, ΔN_{hole} is governed by four different factors, as shown in Fig. 1(c). When the light is turned on, holes are generated and accumulate at a constant rate of G_{light}. These holes also recombine at the bulk silicon region at a rate of R_{bulk}. R_{bulk} is governed by the Shockley–Read–Hall theory with hole density and bulk trap states. These optically generated holes cannot be accumulated indefinitely. When the amount of accumulated holes is large, the front interface is forwardly biased with respect to the n$^+$ S/D region. Therefore, holes diffuse to the n$^+$ region, which determines the maximum hole capacity. Under this situation, the pulse waveform (V_G) is applied to the gate with light illumination. Optically generated holes accumulate at the front interface when a negative V_G (V_L) is applied. These holes then recombine with trapped electrons at the interface traps when the positive V_G (V_H) is applied (this is known as the CP process [6], [7]). Therefore, ΔN_{hole} is affected by the CP process in which the recombination rate by the CP process (R_{CP}) is given as $R_{\mathrm{CP}} = f \cdot A_G \cdot N_{\mathrm{it}}$, where f is the applied pulse frequency and N_{it} is the interface-trap density at the front interface.

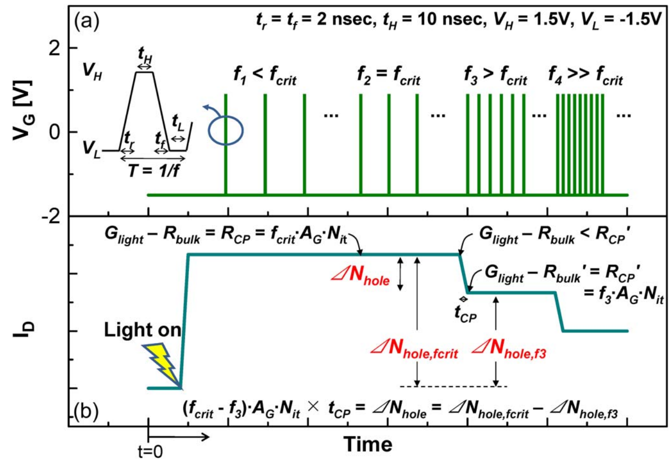

Fig. 2. (a) Biasing level and timing of the applied pulse waveform (V_G), and (b) the expected I_D characteristics according to applied V_G.

Fig. 2(a) shows a schematic of the designed pulse waveform (V_G), and Fig. 2(b) shows the expected I_D characteristics according to the applied V_G. When light is illuminated with a dc bias of $V_G = -1.5$ V, a certain amount of I_D is increased due to the holes that accumulate at the front interface. Subsequently, an ac pulse is applied for the CP process under continuous light illumination. When a pulse of $f = f_1$ is applied, I_D does not change because $G_{\mathrm{light}} - R_{\mathrm{bulk}}$ is still higher than R_{CP}. It should be noted that the CP process can occur within a nanosecond [10]; thus, the biasing time of V_H $(t_H = 10$ ns$)$ is made as short as possible relative to the biasing time of V_L $(t_L > 1$ ms$)$ to remove the uncertain I_D change. This implies that φ_{inv} is not affected by the application of V_H (this is confirmed later). Next, when f reaches f_{crit}, $G_{\mathrm{light}} - R_{\mathrm{bulk}}$ is equal to R_{CP} $(= f_{\mathrm{cirt}} \cdot A_G \cdot N_{\mathrm{it}})$. After exceeding f_{crit} $(f = f_3)$, R'_{CP} $(= f_3 \cdot A_G \cdot N_{\mathrm{it}})$ is higher than $G_{\mathrm{light}} - R_{\mathrm{bulk}}$. Consequently, the accumulated holes are recombined in the CP process, and I_D therefore decreases. However, the decrement of I_D does not occur continuously because R_{bulk} is also changed to R'_{bulk} according to the modulation of the hole density. Therefore, the hole-reduction effect by the CP process can be monitored by I_D only within a specific time (t_{CP}). Here, it needs to be assumed that R_{bulk} is constant during t_{CP} and that it suddenly changes to R'_{bulk} after it passes t_{CP}. Finally, $G_{\mathrm{light}} - R'_{\mathrm{bulk}}$ and R'_{CP} go into equilibrium, which keeps I_D constant. Using the calculated value of ΔN_{hole} from the aforementioned model and the measured value of I_D, N_{it} can be attained by $(f_{\mathrm{crit}} - f_3) \cdot A_G \cdot N_{\mathrm{it}} \times t_{\mathrm{CP}} = \Delta N_{\mathrm{hole}} = \Delta N_{\mathrm{hole,fcrit}} - \Delta N_{\mathrm{hole},f3}$.

Fig. 3(a) shows the measured I_D transient characteristics. The biasing level and timing conditions of V_G are shown in Fig. 2(a). When f_3 $(= 300$ Hz$)$ exceeds f_{crit} $(= 100$ Hz$)$, I_D suddenly decreases to within t_{CP}. From the measured change of I_D and the developed model, the calculated value of N_{it} is 1.26×10^{10} [cm^{-2}], which is in good agreement with the value obtained with a conventional CP measurement through the body

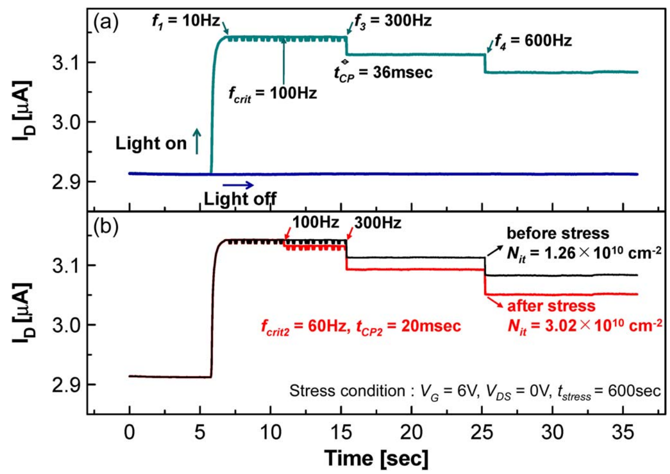

Fig. 3. (a) Measured I_D characteristics by the optically assisted CP process. (b) Measured I_D characteristics after FN stress.

contact [7]. It is noteworthy that I_D remains constant unless the light is illuminated, regardless of the frequency. This implies that the sudden decrement of I_D is only caused by the CP process associated with optically generated holes and that $\varphi_{\rm inv}$ is not affected by the application of V_H. To verify the validity of the proposed optical CP technique, measurements were carried out before and after an electrical-stress test. Fig. 3(b) shows the results obtained after uniform Fowler–Nordheim (FN) stress. A decrease of $f_{\rm crit2}$ and an increase in the change of I_D were observed after the stress test. This clearly corresponds to the increase in the interface-trap density. The calculated poststress trap density is 3.02×10^{10} $[{\rm cm}^{-2}]$, which supports that the optical CP can monitor the change of the interface traps. However, to understand the change of $t_{\rm CP}$ according to the trap density, the aforementioned assumption of $R_{\rm bulk}$ should be modified, and the transient characteristics of $R_{\rm bulk}$ during $t_{\rm CP}$ should be included in the models. This requires further study.

To overcome the limitations of the use of conventional CP, another technique known as a transient CP was previously proposed by Okhonin *et al.* [11]. This technique was successfully demonstrated on partially and fully depleted FB devices [12]. When $N_{\rm it}$ is extracted from the same device by using both the transient CP and optical CP, there is no significant difference (data are not shown). From this result, it can be concluded that the proposed optical CP is a valid technique to extract the $N_{\rm it}$ value. The detail of the comparison between the transient CP and optical CP is left for further study.

III. Conclusion

In summary, an optically assisted CP technique to quantify the interface-trap density in FB devices was demonstrated. In this technique, majority carriers were generated by light illumination and removed via recombination during the CP process. The consequent change in the drain current was used to determine the interface-trap density by the developed analytical model. The proposed technique can provide information pertaining to interface-trap states regardless of the device structure, materials, and dimensions. This is a great benefit, particularly when investigating nanoscale FB devices. However, the developed model is simplified by ignoring the secondary effects: geometric recombination current, local heating, and bulk trap. It may incur uncertainty. Therefore, it needs further comprehensive study for improved accuracy.

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