A Simple Method to Obtain the Generation Lifetime in MOS Capacitors

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Abstract—This paper describes a new simple method for the estimation of the generation lifetime in MOS capacitors fabricated on high resistivity silicon substrates. In this method, the transition between the strong inversion initial steady state and the non-equilibrium deep depletion state occurs by applying a triangular gate voltage. The mathematical model of the proposed method is presented. The generation lifetime value, \( \tau_g = 517 \pm 40 \) \( \mu s \), obtained with our current-triangular sweep voltage method agrees with the \( 510 \pm 30 \) \( \mu s \) value obtained by the \( C-t \) Zerbst method, and the \( 517 \pm 15 \) \( \mu s \) value obtained by using the \( I-C-t \) characteristics for a pulsed MOS capacitor. The results obtained in this work show that the proposed simple method is useful as an express monitoring tool for an estimation of the generation lifetime.

Index Terms Current-Triangular Sweep Voltage Method, non-equilibrium deep depletion, generation lifetime, MOS capacitor.

I. INTRODUCTION

The pulsed metal-oxide-semiconductor (MOS) capacitor transient [1] is the most frequently method used to determine the minority carrier generation lifetime and the surface generation velocity. Several methods for investigate the generation lifetime in MOS capacitor have been developed: current-capacitance \( (I-C-t) \) [1], Zerbst capacitance-time \( (C-t) \) technique [3], and linear sweep techniques [4], among others [6]. The knowledge of the generation lifetime \( \tau_g \) is important for monitoring technological processes for device fabrication based on high-resistivity silicon substrates as photodetectors, particles counters, and charge coupled devices (CCD). This is due to the strong dependence of the device performance on the substrate characteristics such as the crystalline defects density, heavy metal atoms contamination, and the interface state density [1], parameters that can be strongly changed during the chemical and high temperature technological processes.

Unfortunately, those methods mentioned above require the use of specialized and expensive measuring equipment. In the Zerbst technique, the MOS capacitor is pulsed into the deep depletion state. The time-dependent relaxation of the depletion layer width is related to the change in the inversion layer carrier density, and from the capacitance relaxation by thermal electron-hole generation; in this way the minority carrier generation lifetime can be determined. The substrate doping density needs to be known. However, when simultaneous \( C-t \) and \( I-t \) curves are measured, the generation time can be determined without knowing the doping concentration. The equilibrium between the thermal electron-hole generation rate and the linearly varying voltage driving the device into deep depletion is used in the linear sweep technique [4]. A series of \( C-V_G \) curves at different linear sweep rates, \( R \), are necessary to determine the generation lifetime.

In this work, a simpler method for the estimation of the generation lifetime, that requires only a function signal generator and a digital oscilloscope, is proposed. The mathematical modeling of the non-equilibrium processes occurring in the MOS capacitor using such method is described. To validate the model, the generation time obtained with this method is compared with the results obtained with other well-known methods.

II. OPERATING PRINCIPLE

A. Model considerations

In order to obtain the generation lifetime of minority carriers in MOS capacitors by our current-triangular sweep voltage method, the capacitor is connected in series with a function generator having a DC offset voltage and a load resistor \( R_L \). The superposition of the constant (DC) voltage \( U_1 < 0 \) and the triangular voltage signal, with period \( 2T \), is applied to the gate of the MOS capacitor, which was fabricated on an n-type silicon substrate.

![Fig. 1. Time-dependent gate voltage (a) and the current (b) flowing through the circuit.](image)

The output signal is recorded by a digital oscilloscope. Under accumulation, the MOS capacitor presents a capacitance of \( C_{ox} \). The constant negative voltage \( U_1 \) applied to the gate leads the capacitor to a strong inversion initial steady state. The triangular voltage \( U_2(t) \) with the same sign as \( U_1 \) leads the capacitor to a non-equilibrium deep depletion...
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state. The time-dependent gate voltage (a) and the current (b) flowing through the circuit are shown schematically in Fig. 1.

If both surface contributions to the generation are minimized (the peripheral surface and the surface states at the Si/SiO₂ interface), three current components will flow through the circuit: a displacement current \( I_d = C(t) \frac{dU}{dt} \) produced by the variation of the capacitance due to the variation of the depletion region width, a current \( I_p \) due to the generation of carriers from the deep levels inside the depletion region, and a current \( I_{diff} \) due to the diffusion of carriers coming from the neutral volume of the substrate. The sign of the total current is different for the two half periods: at the first half period the total current is \( -I_d - I_p + I_{diff} \) due to the coincidence of their individual signs; on the other hand, at the second half period, the total current changes its sign at a certain time because here \( I_d \) is always positive whereas \( (I_p + I_{diff}) \) is negative.

At the first half-period, the increase of the total negative voltage from \( U_1 \) to \( U_2 \) leads to a time-dependent increase of the depletion region width, from its steady value \( W_{ox} \) (determined by the offset \( U_0 \)) to its maximum at \( t = T \). The thermally generated minority carriers as well as the minority carriers diffusing from the neutral volume fill the potential well created by the increasing negative total voltage, from \( U_1 \) to \( U_2 \), which leads to a decreasing width for the depletion region. If the current components \( I_d \) and \( I_{diff} \) due to the flow of these carriers are not too high, the potential well will not be filled completely, and this process may continue at the beginning of the second half-period. The point where the total current crosses the axis means that \( I_d + (I_p + I_{diff}) \). After this time, \( I_d \) remains being positive and higher than the other two negative contributions; and at the time \( t = t_0 \), and due to the decreasing width of the depletion region to its initial value \( W_{ox} \), the displacement current becomes constant to a value \( I_d = C_{ox} \frac{dU}{dt} \).

**B. Mathematical modeling**

In the current-triangular sweep voltage method, the mathematical modeling of these non-equilibrium processes is useful to determine the carrier generation time in MOS capacitors fabricated on high resistivity substrates. For the mathematical modeling of these non-equilibrium processes, we can use the fundamental equation for the voltage drop in the MOS capacitor at each time. Solving (5) and (4), we obtain the equation \( w(t) \equiv w \): \n
\[
\frac{dw}{dt} = \frac{\epsilon_s \epsilon_0 n_d w}{\epsilon_s n_d \tau_s} - \frac{\epsilon_s \epsilon_0 n_d w}{\epsilon_s n_d \tau_s} + \frac{\epsilon_s \epsilon_0 N_d}{\epsilon_s \epsilon_0 N_d \tau_s}
\]

We can neglect the second term in (5) assuming that

\[
\frac{dU}{dt} \gg \frac{q n_d d w}{\epsilon_s n_d \tau_s}
\]

The correct choice of \( dU/dt \) allows for the use of only the first term in (5) to determine a non-equilibrium depletion width \( w \) in the MOS capacitor at each time. Solving (5) with the condition that a non-equilibrium depletion width \( w(t) = 0 \) at \( U = U_1 \), a simple equation for \( w(t) \) is obtained:

\[
w(t) = \left[ \frac{2 \epsilon_s \epsilon_0}{q N_d} (U(t) - U_1) \right]^{1/2}
\]

Taking into account (1) and (2) for \( U(t) \), the dependence on time for \( w(t) \) for both half periods is determined as:
The generation time ($\tau_g$) may be obtained from (9) for the charge balance at $t = t_x$:

$$C_{\text{ox}}\Delta U \frac{2T-t_e}{T} = \frac{qN_{\text{d}}}{\tau_g} \int_0^t \left( \frac{t}{T} \right)^{1/2} dt + \int_0^t \left( \frac{2T-t}{T} \right)^{1/2} dt$$

(9)

where

$$w_0 = \left( \frac{2\varepsilon_0 \varepsilon_r \Delta U}{qN_{\text{d}}} \right)^{1/2}$$

After integrating, the equation for $\tau_g$ is:

$$\tau_g = \frac{qN_{\text{d}}w_0A}{4T^2 - \left(2/T^{1/2}\right)\left(2T-t_e\right)^{1/2}}$$

(10)

### III. EXPERIMENTAL RESULTS

The experimental data used for the determination of the generation lifetime with this novel method are shown in Fig. 2. The value obtained for the generation lifetime $\tau_g$ according to (10) is 517 ± 40 μs using the results obtained experimentally for $2T = 1.964$ s, $\Delta U = 17.31$ V, $t_x = 1.932$ s, $n_i = 5.1 \times 10^9$ cm$^{-3}$ (at the measured temperature of 15.5 ºC). The parameters of the MOS capacitor with 60/70 nm SiO$_2$/Si$_3$N$_4$ oxide, and aluminum gate, are $A = 0.06$ mm$^2$, $C_{\text{ox}} = 1.9$ nF, $\varepsilon_0 = 11.8$, $\varepsilon_{\text{ox}} = 4.7$, and $N_{\text{d}} = 2 \times 10^{12}$ cm$^{-3}$.

We can clearly identify two sources of error when $\tau_g$ is determined using this method: 1) the precise knowledge of the majority carrier concentration (for the determination of $w_0$, and 2) the precise determination of $t_x$.

### IV. DISCUSSION

In order to validate the proposed method, we must compare our presented results with those obtained using other methods. We show this comparison with those results obtained using two well-known methods for the determination of the generation lifetime. The most common is the Zerbst method for a pulsed MOS capacitor [3], and a $\tau_g = 510 \pm 30$ μs is obtained from the linear part of the Zerbst Plot shown in Fig. 3, using (11) without considering surface generation.

The current-capacitance technique [1] presents an advantage in comparison with the Zerbst technique [3]: in this case it is not necessary to precisely know the majority carrier concentration in the substrate. Thus, according to the current-capacitance technique, the value of $\tau_g$ in the absence of surface generation can be obtained from the next dependence:

$$\frac{1}{1-C(t)/C_{\text{sat}}} = \frac{1}{\tau_g} \left( \frac{1}{C(t)} - \frac{1}{C_{\text{in}}} \right)$$

(12)

Where $C_{\text{in}}$ is the saturated inversion capacitance measured at high frequency. The $I$-$C$ characteristics at 100 kHz are shown in Fig. 4.

In order to use (12) to obtain the generation time, we use the experimental data to generate the plot shown in Fig. 5; from the linear part we extracted $\tau_g = 517 \pm 15$ μs.
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Thus, one can see that the proposed method using a triangular sweep voltage to determine the generation time in MOS capacitor presents a good agreement with those results obtained by using other most common techniques.

We have used \( \tau_g \) instead of its effective value \( \tau_{eff} \) in (8-10) because our MOS capacitor was designed in order to minimize additional effects due to surface generation in the gate perimeter. Furthermore, in this proposed method, the generation lifetime has been estimated with the capacitor initially operating in strong inversion in order to prevent the influence of the generation effects at the Si/SiO\(_2\)/Si\(_3\)N\(_4\) interface under the gate electrode.

CONCLUSIONS

It can be stated that the results presented in this work for obtaining the carriers generation lifetime, using a very simple and non expensive method, delivers values close to those obtained with more complicated techniques. This new method is proposed for monitoring the generation lifetime for processing devices based on high resistivity silicon substrates.

REFERENCES


Fig. 5. Re-plotted data from Fig. 4 used to determine the generation time from the linear part, according to Equation (12).

Fig. 6. Dependence of the generation time on the value of \((2T - t_x)\); the period \(2T\) for the triangular voltage and \(\Delta U\) are 2 s and 10 V, respectively.

The method using a triangular sweep voltage can be used, for instance, as a simple tool for “express monitoring” when a fast/easy determination of \( \tau_g \) is necessary to control technological processes. The generation time can be determined easily from express measurements observed directly on a digital oscilloscope, and using a function generator operating under fixed parameters of the MOS capacitor and the triangular bias such as those shown in Fig. 1. Once the value of \((2T - t_x)\) has been determined, it is easy the monitoring of \( \tau_g \) via the graphical dependence of the generation time on \((2T - t_x)\) according to (8). Fig. 6 shows an example of such dependence that has been used in our processes at different values of the intrinsic carrier concentration that depends on temperature.