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On the difference in the value of surface generation velocity measured in MOS structures by the voltage pulse and double-sweep voltage techniques

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Abstract. It is shown theoretically and experimentally that it is not possible to compare the value of the surface generation velocity in MOS structures, measured by the pulse voltage and double-sweep voltage methods. In the case of the latter method, the surface generation velocity depends on the voltage sweep rate. At low voltage sweep rates the surface is not depleted and surface generation centers are screened by the minority carriers, which results in low surface generation velocity.

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1. Introduction

The trends in VLSI technology towards increased complexity and smaller device dimensions need high quality materials and tight process and device parameters control. Because the generation lifetime, τ_g, and surface generation velocity, S, depend directly on foreign impurities and different types of defects they are of great importance in process and device characterization. Various techniques have been developed to measure the generation lifetime and surface generation velocity. Different researchers use different techniques and very often they have to compare their results with the published ones. An attempt to compare the values of τ_g and S obtained by the use of different techniques with the ones obtained by the method of Zerbst [1] was made by Kang and Schroeder [2].

The purpose of this paper is to show that the value of S measured by the double-sweep voltage method cannot be compared with the one measured by the

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pulse voltage method. In the case of the double-sweep voltage method the value of S depends on the voltage sweep rate.

2. Theory

When a MOS capacitor is pulsed into deep depletion state, it returns to quasi-equilibrium inversion condition as a result of both thermal bulk and surface generation.

The general expression of the well known Zerbst method [1] which gives the relation between the generation parameters and the relaxation of the capacitance is

$$-\frac{\varepsilon_S N_B}{2C_{ox}}\frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2 = \frac{n_i \varepsilon_S}{\tau_g C_F}\left(\frac{C_F}{C} - 1\right) + n_i S, \tag{1}$$

where ε_S is the semiconductor dielectric constant, N_B is the impurity concentration, C_F is the final inversion capacitance, n_i is the intrinsic carrier concentration and C_{ox} is the oxide capacitance.

The slope of the plot $-(d/dt)(C_{ox}/C)^2$ versus $(C_F/C - 1)$ is inversely proportional to τ_g, while the intercept is proportional to S.

When a depleting voltage ramp in the form

$$V(t) = V_o + \alpha t, \tag{2}$$

where V_o is the offset voltage and

$$\alpha = \pm\frac{dV}{dt} \tag{3}$$

is applied to the gate of a MOS capacitor, a non-equilibrium depletion layer arises and carrier generation starts in this region until the maximum (minimum) voltage is reached. After that there is a decrease of the space charge region width, not only due to the generation of carriers but also due to the increasing (decreasing) of the ramp applied to the gate. For the backward voltage the increase of the capacitance shows a hysteresis in the C-V curve due to the presence of minority carrier charge, Q_i, at the interface. A typical C-V curve with hysteresis is shown in Fig. 1 where V_F and V_R are the forward and backward voltages, corresponding to a given capacitance value. The value of the hysteresis, $\Delta V = V_F - V_R$, depends on the generation lifetime and surface generation velocity for a given sweep rate.

The value of the hysteresis in that case can be expressed as follows:

$$\Delta V = \frac{Q_i}{C_{ox}} \tag{4}$$

or

$$N_i = \frac{C_{ox}\Delta V}{q}, \tag{5}$$

where q is the charge of the electron.

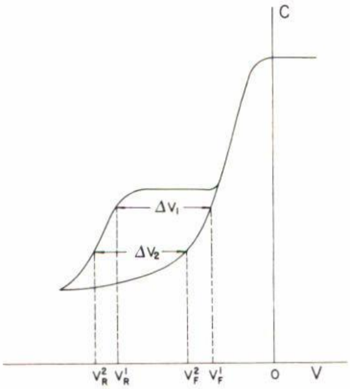

FIGURE 1. C–V curve obtained with the application of a triangular voltage sweep.

Differentiating Eq. (5) with respect to the time we obtain

$$\frac{dN_{\rm i}}{dt}=\frac{C_{\rm ox}}{q}\frac{d(\Delta V)}{dt}=\alpha\frac{C_{\rm ox}}{q}\frac{d(\Delta V)}{dV}. \tag{6}$$

The last term in Eq. (6) can be expressed in the following form [3]:

$$\alpha\frac{C_{\rm ox}}{q}\frac{d(\Delta V)}{dV}=\alpha\frac{C_{\rm ox}}{q}\frac{U_{\rm F}-U_{\rm R}}{U_{\rm F}+U_{\rm R}}, \tag{7}$$

where

$$U_{\rm F}=V_{\rm F}^1-V_{\rm F}^2 \tag{8a}$$

and

$$U_{\rm R}=V_{\rm R}^1-V_{\rm R}^2. \tag{8b}$$

The general expression of the triangular-voltage sweep (or double weep) method [3] is

$$\alpha\frac{C_{\rm ox}}{q}\frac{U_{\rm F}-U_{\rm R}}{U_{\rm F}+U_{\rm R}}=\frac{n_{\rm i}\varepsilon_{\rm S}}{\tau_{\rm g}C_{\rm F}}\left(\frac{C_{\rm F}}{C}-1\right)+n_{\rm i}S. \tag{9}$$

The slope of the plot $(U_{\rm F}-U_{\rm R})/(U_{\rm F}+U_{\rm R})$ *versus* $(C_{\rm F}/C-1)$ is inversely proportional to $\tau_{\rm g}$ and the intercept is proportional to S.

As can be seen, the right hand sides of Eqs. (1) and (9) are equal. Now, we have to present the left hand side of Eq. (9) in such a form that we can compare it with the left hand side term of Eq. (1).

Using the charge neutrality condition in the case when a voltage is applied on the gate of a MOS structure, we can write

$$qN_\mathrm{i} = C_\mathrm{ox}(V - \varphi_\mathrm{S}) - Q_\mathrm{B} - Q_\mathrm{ss} - \phi_\mathrm{ms}, \tag{10}$$

where V is given by Eq. (2), φ_S is the surface potential, Q_B is the depletion layer charge, Q_ss is the equivalent interface charge and ϕ_ms is the difference in the work function between the semiconductor and the gate metal.

Neglecting the voltage drop across the inversion layer and using the depletion approximation we obtain

$$\varphi_\mathrm{S} = \frac{q}{\varepsilon_\mathrm{S}}\int_0^W xN_\mathrm{B}dx, \tag{11}$$

$$\frac{d\varphi_\mathrm{S}}{dt} = \frac{qW}{\varepsilon_\mathrm{S}}N_\mathrm{B}\frac{dW}{dt}, \tag{12}$$

$$Q_\mathrm{B} = q\int_0^W N_\mathrm{B}dx, \tag{13}$$

$$\frac{dQ_\mathrm{B}}{dt} = qN_\mathrm{B}\frac{dW}{dt}, \tag{14}$$

where W is the depletion layer width.

Differentiating Eq. (10) with respect to time and substituting Eqs. (12) and (14) in it, we obtain for the inversion layer charge rate of change

$$\frac{dN_\mathrm{i}}{dt} = \alpha\frac{C_\mathrm{ox}}{q} - \left[\frac{C_\mathrm{ox}W}{\varepsilon_\mathrm{S}} + 1\right]N_\mathrm{B}\frac{dW}{dt}. \tag{15}$$

Using the relation

$$W = \varepsilon_\mathrm{S}\left(\frac{1}{C} - \frac{1}{C_\mathrm{ox}}\right) \tag{16}$$

we obtain from Eq. (15) after some transformations

$$\frac{dN_\mathrm{i}}{dt} = \alpha\frac{C_\mathrm{ox}}{q}\frac{U_\mathrm{F} - U_\mathrm{R}}{U_\mathrm{F} + U_\mathrm{R}} = \alpha\frac{C_\mathrm{ox}}{q} - \frac{\varepsilon_\mathrm{S}N_\mathrm{B}}{2C_\mathrm{ox}}\frac{d}{dt}\left(\frac{C_\mathrm{ox}}{C}\right)^2. \tag{17}$$

Equating the right hand sides of Eqs. (9) and (17) we obtain

$$\alpha\frac{C_\mathrm{ox}}{q} - \frac{\varepsilon_\mathrm{S}N_\mathrm{B}}{2C_\mathrm{ox}}\frac{d}{dt}\left(\frac{C_\mathrm{ox}}{C}\right)^2 = \frac{\varepsilon_\mathrm{S}n_\mathrm{i}}{\tau_\mathrm{g}C_\mathrm{F}}\left(\frac{C_\mathrm{F}}{C} - 1\right) + n_\mathrm{i}S. \tag{18}$$

Equation (9) is the same as Eq. (18) but with the left hand side term represented in a form suitable for our analysis.

Using Eq. (1) and Eq. (18), the surface generation velocity will be given in the case of the Zerbst method by

$$S = -\frac{\varepsilon_S N_B}{2n_i C_{ox}} \frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2 - \frac{\varepsilon_S}{\tau_g C_F}\left(\frac{C_F}{C} - 1\right), \tag{19}$$

and in the case of the triangular-voltage sweep method by

$$S = \alpha \frac{C_{ox}}{qn_i} - \frac{\varepsilon_S N_B}{2n_i C_{ox}} \frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2 - \frac{\varepsilon_S}{\tau_g C_F}\left(\frac{C_F}{C} - 1\right), \tag{20}$$

respectively.

Comparing Eqs. (19) and (20) it can be seen that in the case of the triangular-voltage sweep method, the surface generation velocity depends on the voltage sweep rate α through the first term in the right hand side of Eq. (20).

Let us now clarify the problem from the physical point of view. By analogy with the SRH theory of bulk recombination [4] the single-level surface recombination rate is given by

$$R_S = \frac{v\sigma_{ns}\sigma_{ps}N_{ts}(n_S p_S - n_i^2)}{\sigma_{ns}(n_S + n_{is}) + \sigma_{ps}(p_S + p_{is})}, \tag{21}$$

where

$$\begin{aligned} n_{is} &= \exp\left[\frac{E_{ts} - E_{is}}{kT}\right], \\ p_{is} &= \exp\left[\frac{E_{ts} - E_{is}}{kT}\right], \end{aligned} \tag{22}$$

σ_{ns} and σ_{ps} are the surface electron and hole capture cross sections, respectively, n_S and p_S are the surface electron and hole concentrations, respectively, N_{ts} is the surface trap density, E_{ts} is the surface trap energy level, E_{is} is the intrinsic Fermi level at the surface, k is the Boltzmann constant, T is the temperature and v is the carrier thermal velocity.

Surface generation rate is given also by Eq. (21) and is related to the surface generation velocity by the expression

$$G_S = n_i S. \tag{23}$$

In the case of deep depletion n_S and p_S can be neglected.

As has been shown [5], when an inversion layer starts to form at the surface (*i.e.* when $p_S/\sigma_{ns} \gg p_{is}/\sigma_{ns}$; n_{is}/σ_{ps} for n-type semiconductor), according to Eqs. (21) and (23) the surface generation velocity will be given by

$$S = \frac{v\sigma_{ns} N_{ts} N_i}{p_S}, \tag{24}$$

and the surface hole concentration by

$$p_S = \frac{Q_i(Q_i + 2qN_B W)}{2\varepsilon_S kT}. \tag{25}$$

In the last case it is assumed that the effect of surface trap recharging can be neglected (*i.e.*, when non-equilibrium inversion layer exists or $p_S \gg N_B$).

To obtain the inversion layer charge in the case of the Zerbst method we have to integrate the left hand side of Eq. (1). The result is

$$Q_i = q\int_0^t G(t)\,dt = \frac{q\varepsilon_S N_B}{2C_{ox}}\left[\left(\frac{C_{ox}}{C(0)}\right)^2 - \left(\frac{C_{ox}}{C(t)}\right)^2\right], \tag{26}$$

where $G = G_b + G_S$ and G_b is the bulk generation rate.

As can be seen from Eqs. (24), (25) and (26), the surface generation velocity is time dependent through p_S. Its maximum value, as has been shown [6], can be obtained at $t = 0^+$ when the surface is completely depleted (*i.e.*, when $p_S = n_S = 0$).

In the case of the triangular voltage sweep method Q_i is given by Eq. (4) or Eq. (5) which depends on α for given values of τ_g and S.

To find the influence of α on $p_S(Q_i)$ in an explicit form we have to integrate the left hand side of Eq. (18)

$$\begin{aligned} Q_i = q\int_0^t G(t)\,dt &= \int_0^{t_1}\left[\alpha\frac{C_{ox}}{q} - \frac{\varepsilon_S N_B}{2C_{ox}}\frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2\right]dt \\ &+ \int_{t_1}^{t_2}\left[\alpha\frac{C_{ox}}{q} - \frac{\varepsilon_S N_B}{2C_{ox}}\frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2\right]dt, \end{aligned} \tag{27}$$

where t_1 is the time in forward direction and $t_2 - t_1$ is the time in backward direction of the ramp. Performing the integration we obtain

$$Q_i = \alpha\frac{C_{ox}}{q}(t_2 - 2t_1) + \frac{\varepsilon_S N_B}{2C_{ox}}\left[\left(\frac{C_{ox}}{C(0)}\right)^2 - \left(\frac{C_{ox}}{C(t)}\right)^2\right]. \tag{28}$$

In this case it can be seen from Eq. (28) that the inversion layer charge (or surface hole concentration) depends on α.

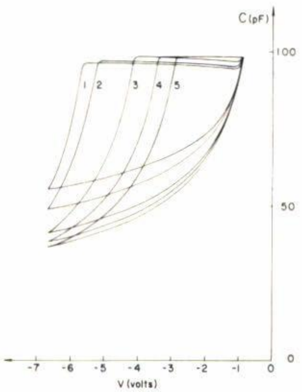

FIGURE 2. Inversion portions of C–V curves obtained for different values of α.

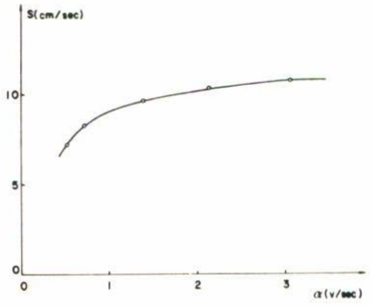

FIGURE 3. Surface generation velocity as a function of the voltage sweep rate.

3. Experiment

The MOS capacitors were fabricated on 2–5 ohm-cm, phosphorous doped, (100) oriented CZ grown Si substrates. The oxidation was performed in dry O_2 with 2% TCA ($C_2H_3Cl_3$) at 1000°C to 540 Å oxide thickness. The oxide thickness was measured with ellipsometer. The oxide on the back side of the wafers was striped. Aluminium dots were evaporated over the top oxide through a metal mask. On the backside of the wafer, aluminium was also evaporated. The wafers were annealed in N_2/H_2 ambient for 45 min at 450°C.

The C–V and C–t curves were obtained with PAR model 410 capacitance meter. WAVETEK 175 waveform generator was used as a voltage sweep source.

In Fig. 2 the inversion portions of the non-equilibrium C–V curves with hysteresis obtained for different values of α are presented. The values of α were 0.54, 0.73, 1.40, 2.14 and 3.08 V/sec for curves 1, 2, 3, 4 and 5, correspondingly. Performing

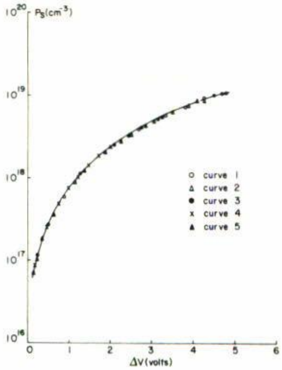

FIGURE 4. Surface hole concentration versus ΔV (data from Fig. 2).

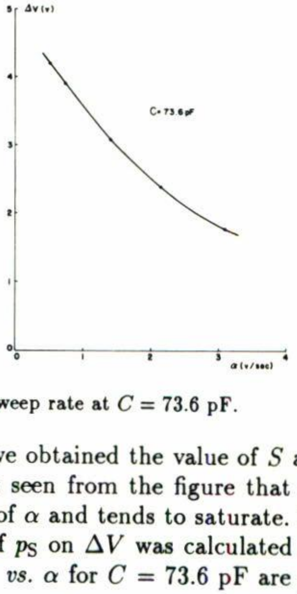

FIGURE 5. ΔV versus voltage sweep rate at $C = 73.6$ pF.

the necessary calculations we obtained the value of S as function of α. The result is presented in Fig. 3. It is seen from the figure that surface generation velocity increases with the increase of α and tends to saturate. From Fig. 2, using Eqs. (5) and (25), the dependence of p_S on ΔV was calculated and the result is presented in Fig. 4. ΔV *vs.* α and p_S *vs.* α for $C = 73.6$ pF are presented in Figs. 5 and 6, respectively.

The measured generation lifetime in this case was 11.3 μsec.

The same sample was used to measure the relaxation C–t curve. Providing the Zerbst analysis using Eq. (1) we calculated $\tau_g = 12.3$ μsec and $S = 11.02$ cm/sec. The generation lifetime measured by both methods coincides in the range of the experimental error ($\approx 8\%$).

Using Eq. (9) and the data from the relaxation C–t experiment we calculated the surface generation velocity as a function of time in the case of Zerbst method. The result is presented in Fig. 7.

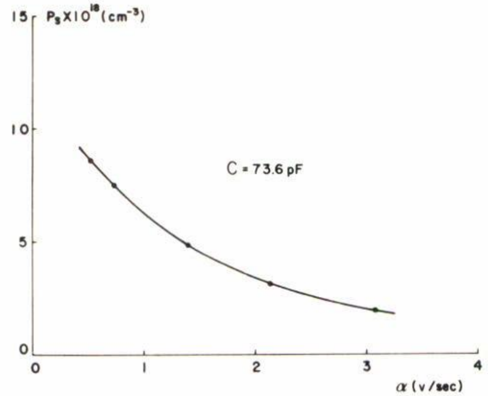

FIGURE 6. Surface hole concentration versus voltage sweep rate at $C = 73.6$ pF.

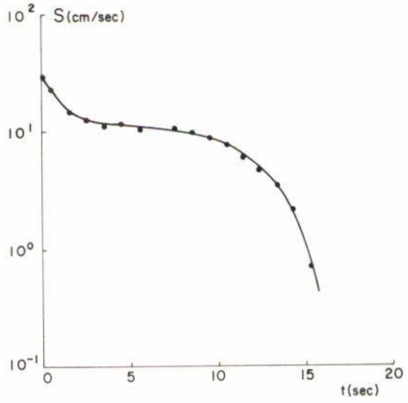

FIGURE 7. Surface generation velocity versus time.

4. Discussion

As shown by Eq. (18) and the experimental results presented in Fig. 3, the surface generation velocity depends on the voltage sweep rate α. The reason for this behavior of S in the case of the triangular voltage sweep method is that it depends on the surface concentration of minority carriers (see Eq. (24)) which in turn depends not only on the thermal generation rate but also on the sign and the value of α (see Eq. (28)). For low values of α the C-V curve obtained with the forward voltage sweep does not correspond to the deep depletion condition. Hence the interface is not completely depleted but has a weak inversion layer (see Fig. 6) which screens surface generation centers and decreases their generation effectiveness. At higher values of α the surface is more depleted and the value of S is higher. Figures 4, 5 and 6 illustrate the effect.

In the case of the Zerbst method, the surface generation velocity is also time dependent through p_S [Eq. (24)], as can be seen from Fig. 7, but in that case the surface concentration of minority carriers is controlled only by the bulk and surface thermal generation rate.

Analyzing the result presented in Fig. 7, it can be concluded that the relatively deep surface centers are responsible for the initial high S value when the value of p_S is low, corresponding to depletion or weak inversion conditions. It is evident that for the rest of the time, at high p_S values, relatively shallow surface donor-like centers ($\sigma_{\mathrm{ns}}/\sigma_{\mathrm{ps}} \gg 1$ and with high $\sigma_{\mathrm{ns}} \times N_{\mathrm{ts}}$ product) are responsible for the surface generation. A similar conclusion was obtained by Gorban *et al.* [5].

It is interesting to see what value of S we measure in practice. Comparing the measured value of $S = 11.02$ cm/sec with the result presented in Fig. 7 it can be concluded that the value of S measured by the Zerbst method corresponds to a surface generation controlled by the shallow surface centers which are responsible for the surface generation activity for the largest part of the relaxation process.

In the case of the double-sweep voltage method the value of S measured at relatively high values of α corresponds to a surface generation velocity controlled by the relatively shallow surface centers.

5. Conclusions

It was shown that it is not possible to compare the value of surface generation velocity measured by the pulse voltage and double-sweep voltage methods because in the latter case the surface generation velocity depends on the voltage sweep rate.

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Resumen. Se muestra, teórica y experimentalmente, que no es posible comparar el valor de la velocidad de generación superficial, medido por los métodos de voltaje pulsado y de doble barrido de voltaje. En el caso del último método, la velocidad de generación superficial depende de la razón del barrido de voltaje. A razones bajas de barrido la superficie no se agota y los centros de generación superficiales son encubiertos por los portadores mayoritarios, lo que da como resultado velocidades bajas de generación superficial.