Analyse of the lateral surface generation in MOS structures

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In the measurements of the generation lifetime, using the method of Zerbst, an effective generation lifetime is measured. According to the model used, this parameter includes the real generation lifetime, surface generation velocity at the depleted lateral space charge region and the diameter of the gate. In this paper is shown that not all but part of the lateral space charge region is fully depleted during the time of measurement. A correction of the model, taking into account the contribution of surface generation velocity only on the depleted lateral space charge region to the generation process, is proposed. The influence of this correction on the generation lifetime obtained by the method of Zerbst is shown.

Keywords: MOS structures; generation lifetime; surface generation velocity.

En mediciones del tiempo de vida de generación usando el método de Zerbst, se determina el tiempo de vida de generación efectivo. De acuerdo con el modelo usado, este parámetro incluye; el tiempo de vida de generación real, la velocidad de generación en la región superficial de la región de carga espacial (scr) lateral y el diámetro de la compuerta. En este trabajo se muestra que no toda el área, sino solo una parte, de la scr superficial lateral permanece completamente desértica de portadores durante la medida. Se propone una corrección al modelo para tomar en cuenta, solo la contribución efectiva de la velocidad de generación en la scr al proceso de generación . Se muestra también, la influencia de esta corrección, sobre el tiempo de vida de generación obtenida por la técnica Zerbst.

Descriptores: Estructuras MOS; tiempo de vida de generación; velocidad de generación superficial.

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1. Introduction

The advance in IC (integrated circuit) complexity and the reduction of minimum device dimensions requires more critical control of IC fabrication processes and the performance of semiconductor devices.

As the generation lifetime and surface generation velocity depend directly on foreign impurities and other kind of crystalline defects they are of great importance in process and device characterization. It is known that the methods of carrier lifetime measurements are more sensitive to the impurities or other kind of crystalline defects than the chemical and physical trace analysis methods [1].

The most frequently used method for determination of generation lifetime and surface generation velocity in MOS structures is the transient capacitance or so called Zerbst method [2]. Using the model of Zerbst, Heiman [3] derived an expression for the capacitance - time (C-t) relationship for fast evaluation of the bulk generation lifetime. Schroder and Nathanson [4] showed that when the surface generation is a significant component of the total carrier generation a modified analysis, which takes into account the surface generation from the lateral surface, must be used. They also showed that it is possible to extract surface generation velocity of a depleted surface. Another modification, which takes into account the bulk generation and the space charge in the lateral spreading of the depletion region around the gate area, was proposed by Rabanni *et al.* [5]. An improved model for the effective generation width was also proposed [6].

In all the above models it is assumed that the lateral part of the surface scr (space charge region) is fully depleted during the transient response. It is well known that surface generation has a maximum value at a depleted surface. Hence, surface generation under the gate diminishes with the time due to the screening effect of the minority carrier inversion layer, while this one at the lateral surface continue at the maximum. It is also assumed in these models that the parameters of the lateral scr are identical to the vertical one. If so, then not all but part of the lateral scr surface will be fully depleted during the entire transient response. This means that the contribution of the lateral surface generation component to the generation process must be reconsidered. This will also affect the evaluation of the generation lifetime obtained by the use of the above methods.

The purpose of this work is to show that during the transient response of an initially fully depleted MOS structure not all but part of the lateral scr is fully depleted. The contribution of the lateral surface generation velocity to the total generation rate is reconsidered and corrected. The influence of this correction on the extracted generation lifetime from the pulsed MOS C-t measurements is demonstrated.

2. Theory

When an MOS capacitor is pulsed into a deep depletion state it returns to the quasi-equilibrium inversion condition as a result of thermal carrier generation in the bulk and at the surface of the device. Let us consider an n-type MOS capacitor pulsed in dark from accumulation into deep depletion. In this case five generation components, shown in Fig. 1, contribute to its return to equilibrium [7]. They are:

1) bulk generation in the scr characterized by the generation lifetime, τ_g;

2) lateral scr generation characterized by the surface generation velocity, S_0;

3) scr generation under the gate characterized by the surface generation velocity, S;

4) quasi-neutral bulk generation characterized by the minority carrier diffusion length, L_n; and

5) back surface generation characterized by the generation velocity, S_c.

Let us assume that at room temperature the diffusion current can be neglected and the wafer thickness is greater than the minority carrier diffusion length. Then the components 4 and 5 can be neglected. In this case the rate of change of the inversion layer carrier density, n_s is related to the carrier generation in the scr by [8]

$$\frac{dn_s}{dt} = \frac{n_i}{\tau_g} W_g + n_i S_0 \frac{A}{A_g} + n_i S, \tag{1}$$

or

$$\frac{dn_s}{dt} = \frac{n_i}{\tau_g} W_g + n_i S_0 W_g \frac{4}{d} + n_i S, \tag{2}$$

where n_i is the intrinsic carrier concentration, $A_g = \pi r^2$ is the gate area, r is the radius and d is the diameter of the gate electrode, $A = 2\pi r W_g$ is the area of the lateral portion of the scr, $W_g = W - W_f$ is the generation region width, W and W_f are the width of the scr and its final value, respectively.

An effective generation lifetime can be defined as [7]

$$\tau_g' = \tau_g \left(1 + \frac{4S_0\tau_g}{d}\right)^{-1}. \tag{3}$$

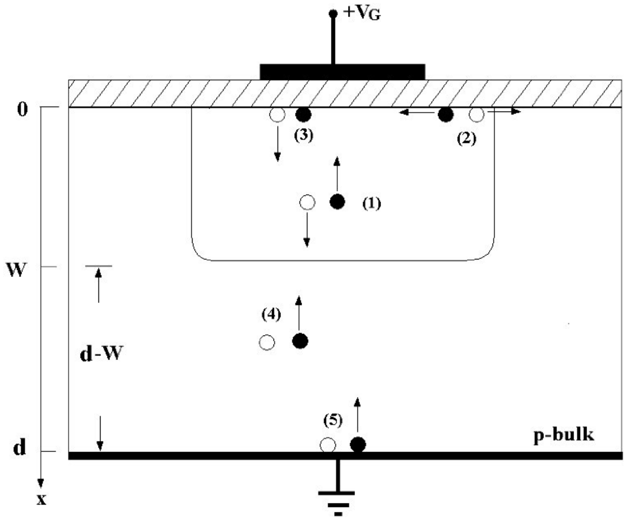

FIGURE 1. Five thermal generation components in a MOS capacitor under deep depletion operation. (1), (2), (3) generation in the space charge region, (4) and (5) generation in the cuasineutral region.

Using Eq. (3), the Eq. (2) can be presented in the form

$$\frac{dn_s}{dt} = \frac{n_i}{\tau_g'} W_g + n_i S. \tag{4}$$

On the other hand, the relation between the inversion layer carrier density, n_s, and the rate of change of the depletion layer, W, can be expressed as [8]

$$\frac{dn_s}{dt} = -N_D \left(1 + \frac{N_D C_{ox}}{\epsilon_0 \epsilon_s} W\right) \frac{dW}{dt}, \tag{5}$$

where N_D is the bulk doping concentration, C_{ox} is the oxide capacitance, and ϵ_s and ϵ_0 are the silicon dielectric constant and the permittivity of the free space, respectively.

Equating the right hand sides of Eqs. (4) and (5), and using the well known relation

$$W = \epsilon_0 \epsilon_s \left(\frac{1}{C} + \frac{1}{C_{ox}}\right), \tag{6}$$

we obtain

$$-\frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2 = \frac{2C^2}{q\epsilon_0\epsilon_s N_D} \times \left[\frac{q\epsilon_0\epsilon_s n_i}{C_f C_{ox} \tau_g'}\left(\frac{C_f}{C} - 1\right) + \frac{q n_i S}{C_{ox}}\right]. \tag{7}$$

The slope of the so-called "Zerbst" plot $(d/dt)(C_{ox}/C)^2$ versus $((C_f/C) - 1)$ gives τ_g' and the intercept gives S. Here S is an effective surface generation velocity which has a maximum value, equal to S_0 at the beginning of the transient process and it decreases with the time due to the screening of g-r (generation - recombination) centers by the minority carriers accumulated at the interface. The relation between S and minority carrier surface concentration, p_s, is given by [9]

$$S = \frac{4S_0}{\pi}\left(\frac{n_i}{p_s}\right) ln\left(\frac{p_s}{n_i}\right). \tag{8}$$

It has been shown that there is almost a linear rise of the minority carrier concentration with the time [10]. This means that surface minority carrier concentration can be related directly with the time

$$p_s = \left(\frac{N_D}{t_f}\right) t, \tag{9}$$

where t_f is the final relaxation time [9].

2.1. Lateral surface generation

Let us first to analyze the processes in an MOS capacitor just after a depleting voltage pulse is applied on the gate. Collins and Churchill [10] showed that in that case the surface under the gate inverts in a very short time (of the order of 10^{-3} sec) compared with the observed capacitance relaxation time (of the order of 10 - 100 sec). Then the simple assumption for the volume concentration of minority carriers at the surface after the first milliseconds,

$$p_s \ll n_i, \tag{10}$$

is no longer valid at the surface under the gate of the MOS capacitor. As they have shown, after the pulse is applied three distinct regions, shown in Fig. 2 [10], can be revealed: the dielectric relaxation time, the depletion time, and the equilibration time. During the initial dielectric relaxation time on the order of 10^{-12}–10^{-9} sec, the majority carriers deplete, building up the depleted surface scr.

During the depletion time on the order of 10^{-9}–10^{-2} sec, surface potential is relatively constant. The equilibrium time starts at about 10^{-2} sec. This fact was experimentally confirmed by Wei and Simmons [11]. As the time passes the device starts to stabilize. During this time the minority carriers grow up to a value compatible to the bulk doping density and start to create an inversion layer until the device comes to equilibrium.

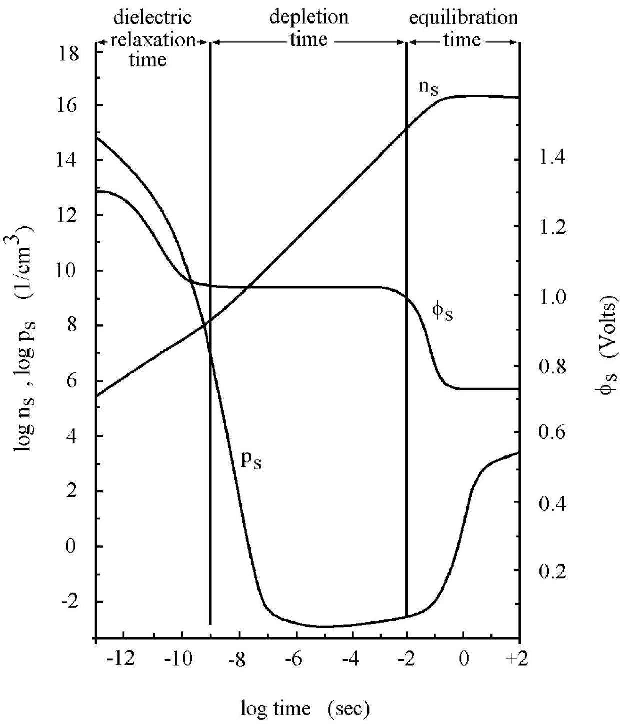

FIGURE 2. n_s, p_s and surface potential, ϕ_s, versus time for a MOS capacitor pulsed from flat band to inversion.

The minority carrier distribution with the time is presented in Fig. 3 [10]. As can be seen from Figs. 2 and 3 for a time greater than 0.01 sec, corresponding to the measurement of the capacitance transient, the surface is screened by the minority carriers with concentration compatible with that of the doping one. This means that the value of surface generation will be quite low compared to that at the depleted surface. The change of the effective surface generation with the minority carrier surface concentration and with the time, during the equilibration period, according to Eqs. (8) and (9) is presented in Figs. 4 and 5, respectively. As can be seen from these figures the effective surface generation is very sensitive to the surface carrier concentration and drops very rapidly with the time.

However, as it was already pointed out, in the models above it is assumed that the parameters of the lateral scr are identical to the vertical one. This means that the distribution of the minority carriers along the lateral part of the scr is the same as that presented in Fig. 3, but the origin of the coordinate system is at the S_i-S_iO_2 interface and the vertical axe is at the edge of the gate electrode. This means that during the time of measurements, on a part of the lateral surface, minority carrier concentration will be much greater than the intrinsic carrier concentration. For this part of the lateral surface area surface generation will be lower than that corresponding to the fully depleted surface, S_0. Indeed, from Fig. 3 it is seen

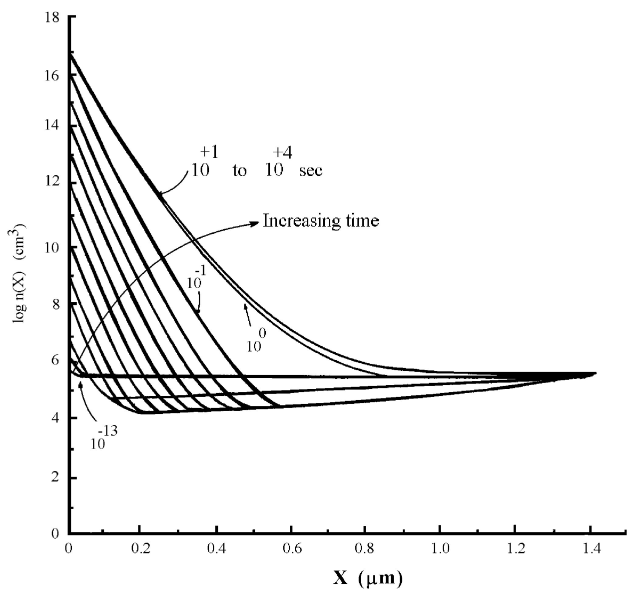

FIGURE 3. Logarithm of minority carrier concentration versus depth with the time as parameter [10].

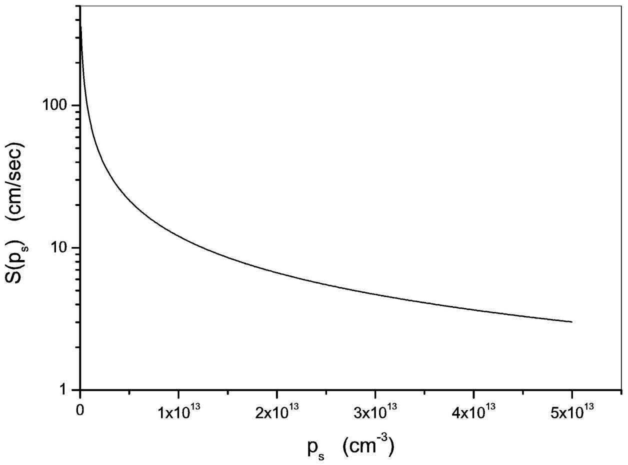

FIGURE 4. Effective surface generation, S, as a function of minority carrier surface concentration, p_s, for $S_0 = 1000$ cm/sec.

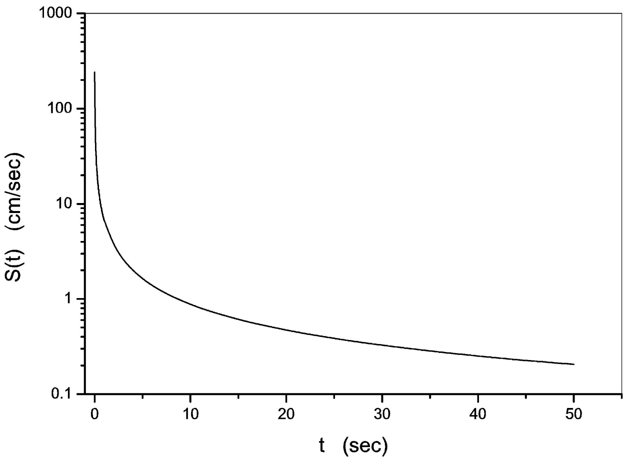

FIGURE 5. Effective surface generation as a function of time for $S_0 = 1000$ cm/sec and $t_f = 50$ sec.

that for a time ≥ 1 sec to a distance of approximately 0.25μm from the surface (or from the edge of the gate electrode) the concentration of the minority carriers is greater than n_i. This part is approximately $1/4$ of the scr ($W \approx 1\mu$m).

At the rest of the lateral scr ($\approx 3W/4$) surface generation velocity must be that corresponding to the fully depleted surface, *i.e.* S_0. According to this approximation and taking into account the contribution only of the depleted surface to the generation current we can write Eq. (3) in the form

$$\tau_g' = \tau_g \left(1 + \frac{3S_0\tau_g}{d}\right)^{-1}. \qquad (11)$$

Before to proceed further it will be useful to calculate τ_g' versus τ_g with S_0 as parameter, using Eq. (3). The result is presented in Fig. 6. As can be seen from the figure, for approximately $\tau_g > 5 \times 10^{-6}$ sec at S_0 = 100 cm/sec and for $\tau_g > 10^{-5}$sec at S_0 = 1000 cm/sec, τ_g' does not depend on the τ_g. According to Eq. (3) [or Eq. (11)], this is due to the fact that the second term in these equations becomes much greater than 1, *i.e.*, $\tau_g' \approx \tau_s$ (surface lifetime, $\tau_s = d/4S_0$) and τ_g' practically does not depend on τ_g.

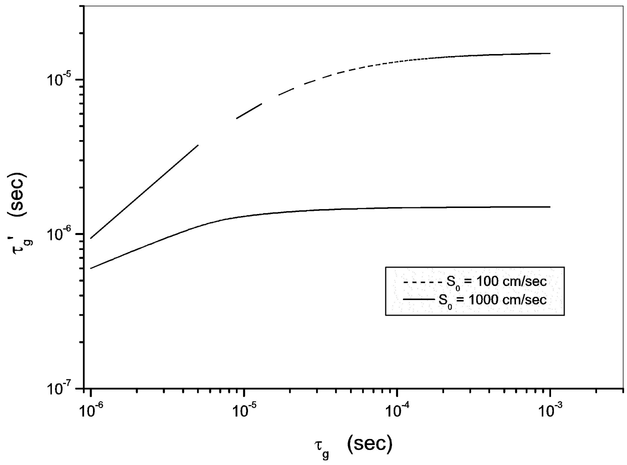

FIGURE 6. Effective generation lifetime versus generation lifetime for $S_0 = 100$ (dash line) and 1000 (full line) cm/sec and $d = 6 \times 10^{-3} cm^2$.

Taking into account these results and according to the models given by Eqs. (3) and (11), τ_g as a function of τ_g' was calculated. The results are presented in Figs. 7 and 8. According to Fig. 7, for S_0 = 1000 cm/sec, with the increase of the measured effective generation lifetime the difference in the real generation lifetime between the two models increases. While for low values of the effective generation lifetime the difference can be neglected, for high values of τ_g' ($\approx 10^{-5}$ sec) the error can be more than one order of magnitude. With the decrease of S_0 the difference between the two models decreases and for S_0 = 100 cm/sec it is very small, as can be seen from Fig. 8.

3. Conclusions

In the measurements of the generation lifetime, using the method of Zerbst, an effective generation lifetime is measured. According to the model used, this parameters include the real generation lifetime as well as surface generation velocity on the depleted lateral scr.

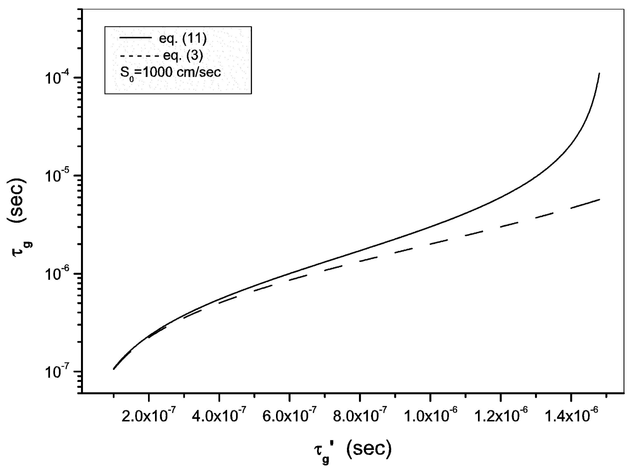

FIGURE 7. τ_g as a function of τ_g' , according to the two models (Eqs. (3) and (11)) for $S_0 = 1000$ cm/sec.

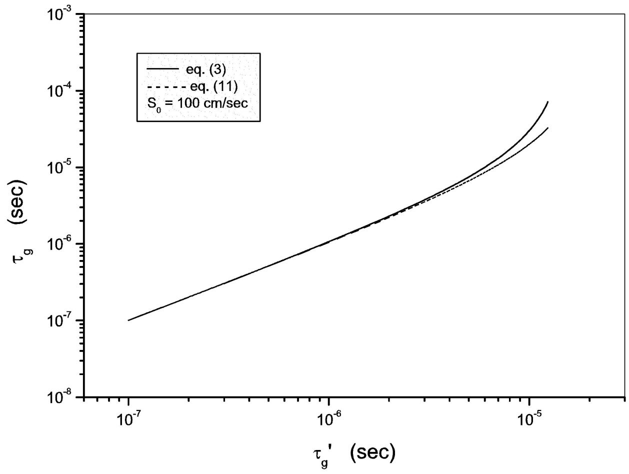

FIGURE 8. τ_g as a function of τ_g' , according to the two models given by Eqs. (3) and (11) for $S_0 = 100$ cm/sec.

Using the transient analysis of the vertical scr [10] it has been shown that not all of the lateral scr is fully depleted during the measurement time. A correction of the model, taking into account the contribution of surface generation at the depleted lateral scr, is proposed. The influence of this correction on the real generation lifetime is shown.

According to the analysis it is important to interpret with care the measured effective generation lifetime because the real one can differ from it. The interpretation must be done carefully mainly in the cases of; high effective generation lifetime, small diameter of the gate electrode and high surface generation velocity. The analysis above can be useful in process and device characterization.

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