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Influence of surface generation velocity and field-enhanced carrier generation on the measured generation lifetime and relaxation time constant in MOS structures

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Today's high quality semiconductor materials are characterized with generation lifetimes in the range 10^{-3}– 10^{-2} sec. This requires re-examination of the influence of some factors on the correct extraction of generation lifetime with the measurement techniques used. Surface generation velocity and field-enhanced carrier generation influence on the measured generation lifetime and relaxation time constant in MOS structures. In the present work, analysis of this influence is presented. It is shown how a simple interpretation of the experimental data can introduce a large error in the determination of these parameters. The influence of all factors must be taken into account.

Keywords: Field-enhanced carrier generation; surface generation velocity; MOS structures.

Los materiales semiconductores de alta calidad se caracterizan actualmente por tener tiempos de vida de generación en el intervalo de 10^{-3} a 10^{-2} segundos. Este hecho demanda hacer una reconsideración de la influencia que ciertos factores pueden tener en la correcta obtención del tiempo de vida de generación, con las técnicas de medición que actualmente se emplean. Particularmente, la velocidad de generación de superficie y la generación de portadores acrecentada por campo influyen en el tiempo de vida de generación y la constante de tiempo de relajación en estructuras MOS. En este trabajo se presenta un análisis de esta influencia. Se muestra cómo una interpretación simple de los datos experimentales puede generar un error considerable en la determinación de estos parámetros. La influencia de todos los factores debe ser tomada en cuenta.

Descriptores: Generación de portadores acrecentada por campo; velocidad de generación superficial; estructuras MOS.

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1. Introduction

Generation lifetime and surface generation velocity are important parameters for process characterization and for analyzing the performance of different semiconductor devices as well as for the design of new ones. The pulsed MOS capacitor transient response to a depleting voltage step [1] is the most frequently used method to determine these parameters. Other non-pulse methods such as the linear [2] or the sine [3] voltage sweep methods, the reverse characteristics of a p-n junction [4], the reverse-bias current versus gate voltage characteristics exhibited by a gate-controlled diode [5] are also used. The various pulse and sweep voltage MOS methods and models are reviewed in Ref. 6.

However, the increasing demand on material quality and on semiconductor device performance calls for a re-examination of some measurement techniques and accuracy of the extracted generation lifetime. For instance, it was shown [7] that for a correct interpretation of pulsed MOS C-t and p-n junction leakage current measurements, the diffusion current component should be taken into account. If not, in some cases like that of lifetime measurements in intrinsic gettered samples, an error as high as a factor of 10 can occur. The importance of lifetime measurements requires a detailed analysis of different factors, which can influence on them.

In the present work, we have investigated the influence of field-enhanced carrier generation and surface generation velocity on the generation lifetime extracted from the pulsed MOS C-t measurements. The influence of surface generation velocity and field-enhanced carrier generation on the relaxation time constant of a MOS capacitor in dark and under illumination is also investigated.

2. Transient analysis

2.1. Carrier generation

Let us consider an n - type MOS capacitor. When a negative voltage step is applied on the gate electrode the capacitor is driven in a deep depletion. As the time progresses the depletion region narrows down as a result of thermal and external generation of electron – hole pairs and the device returns to its quasi – equilibrium inversion state. Five generation components that contribute to its return to equilibrium can be defined [8]. They are:

1) thermal bulk generation in the space charge region (SCR), U_1;

2) thermal surface generation, U_2: a) in the lateral space charge region at the SiO_2-Si interface, b) under the gate;

3) thermal surface generation at the quasi-neutral bulk surface, U_3;

4) thermal bulk generation in the quasi-neutral bulk, U_4; and

5) external generation, U_5. The total generation rate per unit area can be defined as a sum of all these components

$$U = U_1 + U_2 + U_3 + U_4 + U_{ph}. \tag{1}$$

The various generation rates are given by the following equations:

$$U_1 = \frac{n_i}{\tau_g}\left(W - W_F\right), \tag{2}$$

where n_i is the intrinsic carrier concentration given by [9]

$$n_i = 3.87x10^{16} T^{1.5} \exp\left(-\frac{0.605}{kT}\right), \tag{3}$$

$\tau_g$is the generation lifetime, $W_g = W - W_F$ is the generation region width, where W and W_F are the width of the SCR and its final value, respectively, k is the Boltzmann's constant and T is the temperature. Here we assume for simplicity that the generation region width is $W - W_F$. It is well known that this assumption underestimates the real W_g [10], but it is simple and widely accepted [11].

$$U_{2a} = n_i S_0 \frac{A}{A_g}, \tag{4}$$

where S_0 is the surface generation velocity for a depleted surface, $A = 2\pi r W_g$ is the lateral portion of the SCR [11], $A_g = \pi r^2$ is the gate area and r is the radius of the gate electrode. Moreover

$$U_{2b} = n_i S, \tag{5}$$

where S is the time varying surface generation velocity, under the gate electrode. At the beginning and at the end of the relaxation process S is a fast varying function of the time. It was shown that the surface under the gate inverts for a very short time (10^{-3} – 10^{-2} sec) [12]. However, S corresponding to the linear part of the Zerbst plot is a slow varying function of the time, practically constant, but less than S_0[13]. Carriers generated at the quasi-neutral bulk surface can only contribute to the SCR neutralization if that surface is within a diffusion length from the edge of the SCR. Otherwise they recombine before reaching the SCR. In this case the components 3 and 4 are coupled [8]

$$U_3 + U_4 = \frac{n_i^2 D_p}{N_D L_p}, \tag{6}$$

where

$$D_p = \mu_p \frac{kT}{q} \tag{7}$$

is the diffusion constant,

$$\mu_p = 495\left(\frac{300}{T}\right)^{2.2} \tag{8}$$

is the mobility [14],

$$L_p = \sqrt{D_p \tau_r} \tag{9}$$

is the diffusion carrier length and τ_r is the recombination lifetime. In Eq.(6) we use L_p instead of the effective diffusion length L_p^* because we assume that in our case the wafer thickness d $>> L_p^*$ [8].

The generation rate for optical excitation is given by

$$U_{ph} = \eta N_{ph}, \tag{10}$$

where N_{ph} is the photon flux and η is the quantum efficiency, where the effects of reflections at the surface are included.

If we substitute Eqs. (2)-(6) in Eq. (1) we obtain the total generation rate in dark (U_{ph} = 0):

$$U = \frac{n_i}{\tau_g} W_g + n_i S_o \frac{A}{A_g} + n_i S + \frac{n_i^2 D_p}{N_D L_p} \tag{11}$$

or

$$U = \frac{n_i}{\tau_g} W_g + n_i S_o W_g \frac{2}{r} + n_i S + \frac{n_i^2 D_p}{N_D L_p}. \tag{12}$$

An effective generation lifetime and surface generation velocity can be defined as [7]

$$\tau_g^* = \tau_g \left(1 + \frac{2 S_0 \tau_g}{r}\right)^{-1} \tag{13}$$

and

$$S^* = S + \frac{n_i D_p}{N_D L_p}. \tag{14}$$

Using Eqs. (13) and (14), Eq. (12) can be presented in the form

$$U = \frac{n_i}{\tau_g^*} W_g + n_i S^*. \tag{15}$$

The rate of change of the inversion layer carrier density n_s is related to the carrier generation in the SCR and in the quasi–neutral region:

$$\frac{dn_s}{dt} = U, \tag{16}$$

where U is given by Eq. (12)

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

$$\frac{dn_s}{dt} = -N_D \left(1 + \frac{N_D C_{ox}}{\varepsilon_0 \varepsilon_s} W\right) \frac{dW}{dt} \tag{17}$$

Equating the right hand sides of Eqs. (16) and (17) and using the well known relation

$$W = \varepsilon_0 \varepsilon_s \left(\frac{1}{C} - \frac{1}{C_{ox}}\right) \tag{18}$$

we obtain

$$-\frac{d}{dt}\left(\frac{C_{ox}}{C}\right)^2 = \frac{2C^2}{q\varepsilon_0\varepsilon_s N_D} \times \left[\frac{q\varepsilon_0\varepsilon_s n_i}{C_F C_{ox}\tau_g^*}\left(\frac{C_F}{C} - 1\right) + \frac{q n_i S^*}{C_{ox}}\right] \tag{19}$$

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^*.

2.2. Relaxation time constant

The relaxation time constant of an MOS capacitor in dark is [15]

$$T^d = \frac{N_D}{n_i}\tau_g^* \tag{20}$$

However, the generation rate for unit volume is

$$G = \frac{n_i}{\tau_g}$$

Then Eq. (20) becomes

$$T^d = \frac{N_d}{G^d}. \tag{21}$$

The relaxation time constant of an MOS capacitor under illumination is [16]

$$T^l = T^d \frac{n_i}{n_i + G_{ph}\tau_g^*}, \tag{22}$$

where G_{ph} is the optical generation rate per unit volume.

Using Eqs. (20) and (21), Eq. (22) can be represented in the following form

$$T^l = \frac{N_D}{G^d + G_{ph}} \tag{23}$$

Using Eq.(15) we can define an effective volume generation rate as

$$G_{eff}^d = \frac{n_i}{\tau_g'} + \frac{n_i S^*}{W_g}. \tag{24}$$

Substituting Eqs. (13) and (24) in Eq.(22) we have finally for the relaxation time constant of an MOS capacitor under illumination

$$T^l = \frac{N_D}{\dfrac{n_i}{\tau_g}\left(1 + \dfrac{2S_0\tau_g}{W_g}\right) + \dfrac{n_i}{W_g}S + G_{ph}}. \tag{25}$$

2.3. Field-enhanced carrier generation

According to the Pool-Frenkel theory [17] the thermal ionization process of Coulombic centers is affected by an applied electric field. In the light of this theory the generation lifetime can be written as

$$\tau_g(E) = \tau_g(0)\exp\left(-\alpha\sqrt{E}\right), \tag{26}$$

where $\tau_g(0)$ is the generation lifetime at zero electric field,

$$\alpha = \frac{\beta}{kT} \quad \text{and} \quad \beta = \sqrt{\frac{q^3}{\pi\varepsilon_{si}}} \tag{27}$$

are the Pool – Frenkel coefficient and the Pool – Frenkel constant, respectively; q is the charge of the electron, ε_{si} is the dielectric permitivity of silicon and E is the electric field given by

$$E = \frac{qN_D W_g}{\varepsilon_{si}} \tag{28}$$

In the case of field independent carrier generation ($\alpha = 0$) $\tau_g = \tau_g(0)$, while for a field-enhanced carrier generation τ_g must be replaced with $\tau_g(E)$ (Eq.(26)) in the above equations.

3. Numerical results and discussion

The calculations in this work are made with the following typical parameters: N_D=10^{15} cm^{-3}, A=10^{-2} cm^2, $G_{ph} = 10^{12}$ cm^{-3}/sec, $W_g = 10^{-4}$ cm and $\alpha = 8.6x10^{-3}$ (cm/V)$^{1/2}$. To simplify the analysis we have assumed a constant surface generation velocity under the gate $S = 0,1$ cm/sec, corresponding to the values in the present day MOS devices. As it was mentioned above, during the transient response of a pulsed MOS capacitor, corresponding to the linear part of the “Zerbst” plot, S is practically constant and is much less than S_0. It is also assumed that the temperature of 300 K and τ_r are sufficiently high so that the diffusion current (the third term in the right hand side of Eq.(12)) can be neglected, *i.e.*, $S^* = S$in Eq.(14).

The normalized generation lifetime $\tau_g^*/\tau_g(0)$ as a function of S$_0$ and $\tau_g(0)$ as a parameter for the case of field independent and field-enhanced carrier generation is plotted in Figs. 1 and 2, respectively. It is seen from the figures that the effective lifetime decreases with the increase of S_0. For generation lifetime in the range of 10^{-3}-10^{-2} sec, corresponding to the today’s processing techniques and high quality materials, the deviation is high and can provoke large error in the interpretation. This means that in practice if we measure, for instance, τ_g^*= 2.2x10^{-3}sec at S_0 =10 cm/sec the real value will be $\tau_g(0)$=10^{-2} sec (α= 0), *i.e.* the error is 78%. For

S_0= 1 cm/sec and α= 0 the error is 20%. In the case of field-enhanced carrier generation (Fig.2) the influence of S_0 is less.

The relaxation time constant versus generation lifetime dependence with S_0 as a parameter of an MOS capacitor in dark, for the cases of field independent and field-enhanced generation, is presented in Figs. 3 and 4, respectively. As can be seen from the figures the relaxation time constant increases with the generation lifetime and decreases with S_0. It is also seen that for today's high quality materials, with $\tau_g(0)\geq 10^{-3}$sec, the relaxation time is very long and a very long measurement time is needed. This is one of the problems in the process control, where the generation lifetime in a large number of MOS capacitors must be measured.

It is also seen from the figures that in the same generation lifetime range, the relaxation time constant in dark, T^d, is strongly affected by the surface generation velocity, because of its contribution to the total generation current. In the case of field-enhanced generation (Fig. 4) T^d versus $\tau_g\,(0)$ dependence is steeper and the influence of S_0 is less. In Figs. 5 and 6 is plotted the relaxation time constant T^l versus $\tau_g\,(0)$, with S_0 as a parameter, for an MOS capacitor under illumination. The behavior of T^l is the same as that of T^d in Figs. 3 and 4, but in this case $T^l < T^d$ due to the contribution of the additional component G_{ph} to the generation current. This effect has been proposed as a method for reducing the measurement time of τ_g in high quality MOS structures [18].

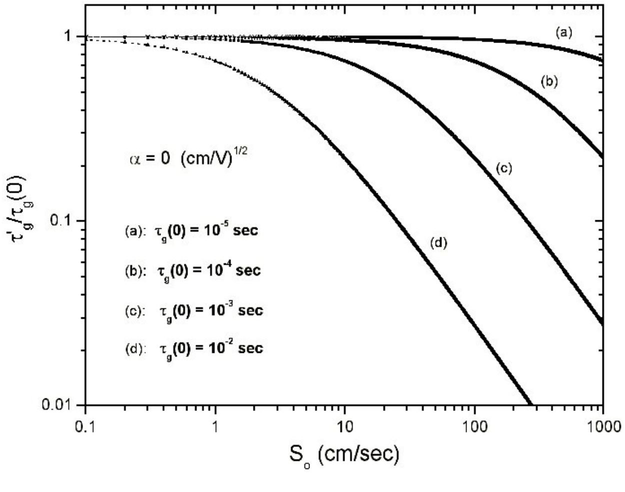

FIGURE 1. Normalized generation lifetime versus surface generation velocity with the generation lifetime as a parameter.

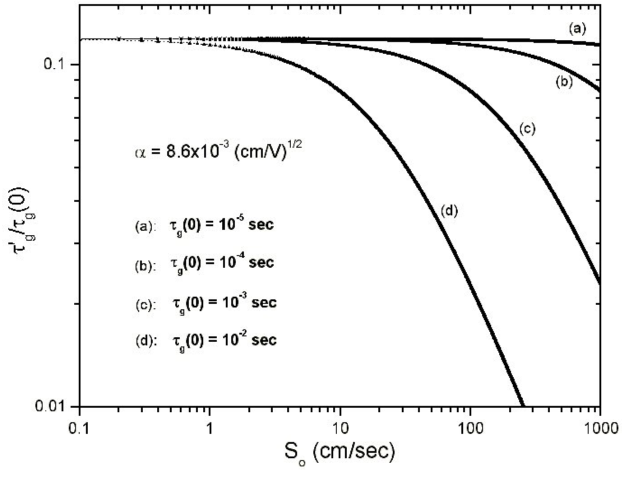

FIGURE 2. Normalized generation lifetime versus surface generation velocity with the generation lifetime as a parameter for field-enhanced generation.

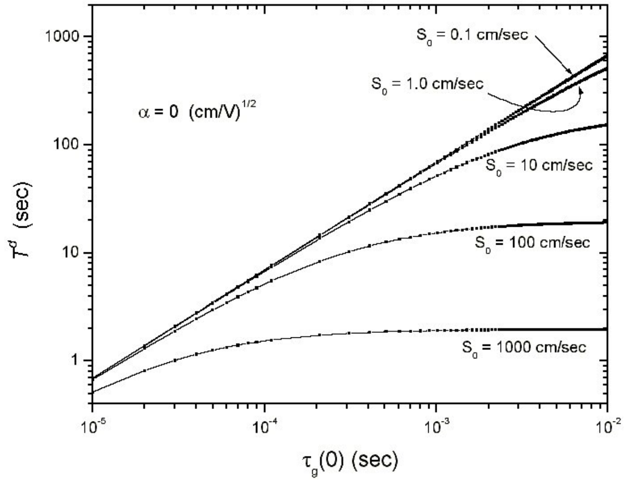

FIGURE 3. Relaxation time constant versus generation lifetime with the surface generation velocity as a parameter.

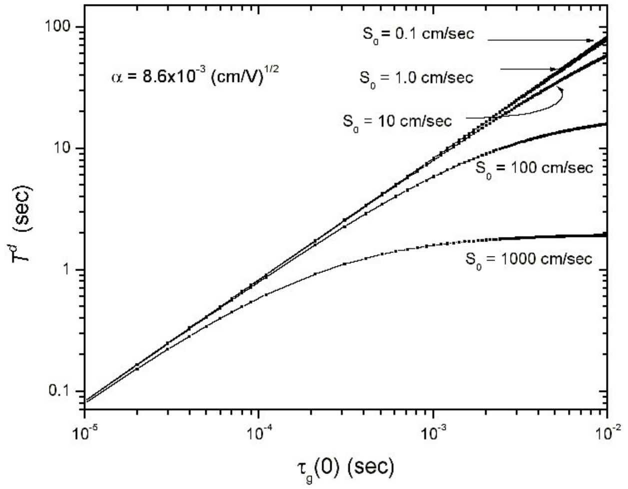

FIGURE 4. Relaxation time constant versus generation lifetime with the surface generation velocity as a parameter for field-enhanced generation.

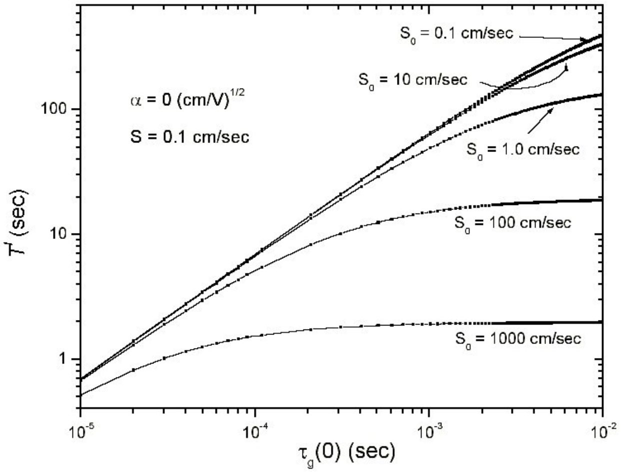

FIGURE 5. Relaxation time constant under illumination versus generation lifetime with the surface generation velocity as a parameter.

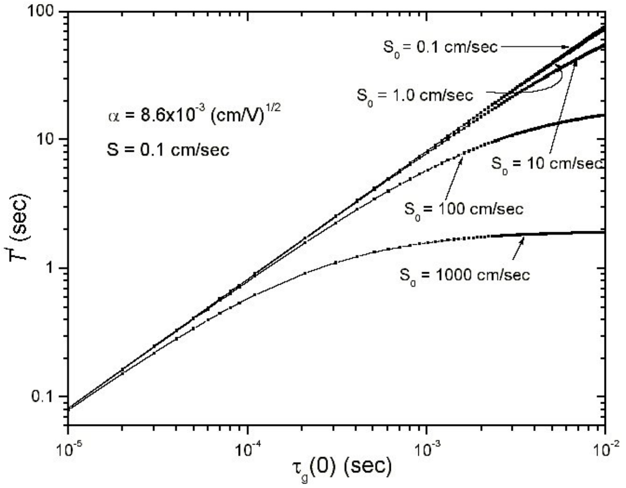

FIGURE 6. Relaxation time constant under illumination versus generation lifetime with the surface generation velocity as a parameter for field-enhanced generation.

4. Conclusions

In this work the influence of surface generation velocity and field-enhanced carrier generation on the generation lifetime extracted by the Zerbst method and on the relaxation time constant of MOS structures was investigated. It shown that there are cases when the simple interpretation of the experimental data can introduce a large error in the estimation of the real generation lifetime. The strongest influence of surface generation velocity on the real generation lifetime is in the case of field independent carrier generation. The difference between the measured effective generation lifetime and the real one increases with S in both cases.

Surface generation velocity, because of its contribution to the total generation current, has also strong influence on the relaxation time constant of MOS structures. Very often, in the case of process control, the measured generation lifetime is assumed as a real one. However, as it was shown, due to the influence of the above factors, the effective generation lifetime can differ essentially from the real one. This information can be useful for process control, for design of new semiconductor devices and/or for development of new methods of investigation.

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