SURFACE RECOMBINATION *VIA* INTERFACE DEFECTS IN FIELD EFFECT TRANSISTORS

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Recombination current at the oxide-semiconductor interface of metal-oxide-semiconductor devices has been analyzed and compared with the experimental result. The activity of interface traps is dependent on the energy level and on the operating conditions. A model is shown to be powerful to describe the effect of energy level of bulk recombination centers on the values of reverse recombination current.

Keywords: Recombination current; oxide semiconductor; energy level

1. INTRODUCTION

The growing interest in the electronic properties of defects in silicon dioxide and at $Si-SiO_2$ interface appears with the observed radiation damages in metal-oxide-semiconductor (MOS) devices used in space applications. The high electric field sustained by oxide layers of the very large scale integration MOS devices leads to carrier injection into SiO_2 layers used as gate insulators. This can generate states at the

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$Si-SiO_2$ interface, and trapping sites in the oxide layer (considered as process induced defects). Similar defects have been seen after device irradiations (radiation induced defects). The density of defects grows with the number of recombination events. The analysis of the induced degradation of electrical properties of MOS devices requires information to be determined experimentally.

MOS gate-controlled *p-n* junctions have been extensively used to investigate surface recombination current in planar diffused devices and a theoretical relation between the junction current and the gate voltage, V_G, has been derived by many workers [1, 2]. The importance of energy level of bulk recombination centers E_t compared to the intrinsic Fermi level E_i on variations of surface recombination current of MOS is not discussed in detail, particularly, no analytical approach is made. For detailed discussion of steady recombination current of MOS structure, impurities at a single energy level are usually considered [3−5]. Reduced forms [6−9] of surface recombination rate, U_s, of electrons or holes have been considered when taking into account operating conditions and carrier or trap density approximations in order to make manageable calculations. In order to obtain a complete theoretical relation between the current and the energy level of bulk recombination centers E_t, it is necessary to consider the whole expression of the steady-state recombination rate.

In the present paper we discuss the effect of energy level of bulk recombination centers on surface recombination current. The method is based on the analysis of forward current-voltage characteristics of the body-drain junction of metal-oxide-semiconductor field-effect transistor (MOSFET) considered as a gate controlled diode. We found that impurities can considerably change the values of the reverse recombination current.

2. MODELLING

In order to investigate non-ideal processes, the model considers the body-drain *n-p* junction of a MOSFET. The junction is said to be gate controlled since an applied gate bias makes it possible to modify the carrier concentration. The conduction band at the surface may be brought close to the Fermi level, producing a depleted layer at the

surface under the gate. A surface recombination current appears, increasing with the gate voltage. Generation and recombination of electrons and holes take place at crystal lattice dislocations, impurity located atoms, surface defects and interface states. The analysis is based on the description of the current-diode characteristics of diode devices.

2.1. Diode Characteristics

The current–voltage $I(V)$ characteristics of the forward biased n-p junctions is conveniently described [10, 11] by the implicit equation

$$
\begin{aligned}
I = {} & \frac{V + R_s I}{R_{sh}} + I_{01} \cdot \left[\exp\left(\frac{q}{KT}(V + R_s I) \right) - 1 \right] \\
& + I_{02} \cdot \left[\exp\left(\frac{q}{2KT}(V + R_s I) \right) - 1 \right]
\end{aligned}
\tag{1}
$$

where R_s and R_{sh} are the series and shunt resistances, I_{01} and I_{02} are known as the reverse currents. The I_{01} component is obtained by modelling diffusion and radiative recombination of minority carrier across the diode neutral layer. The I_{02} component is a result of recombination and this contribution is dominant at low bias. Theoretical works [12] have shown that this contribution appears when minority carrier concentrations are of the order of the majority carrier concentrations. Surface recombination has been suspected [3] as a major source of I_{02} type current. There are two main assumptions that lead to a $2KT$ dependence for surface recombination current. First, the ratio of the electron to hole concentration at the surface is close to unity. Second, the quasi-Fermi levels are flat between the bulk and the surface. The surface recombination current depends on both the applied voltage and the energy level of bulk recombination centres as it will be shown below.

2.2. Recombination Reverse Current

The schematic diagram of the body-drain junction of a MOSFET is shown in Figure 1, where the field induced and junction depleted regions are shaded. This study is performed with a positive gate potential V_G (below the threshold level, 0 to 3 V), a negative drain
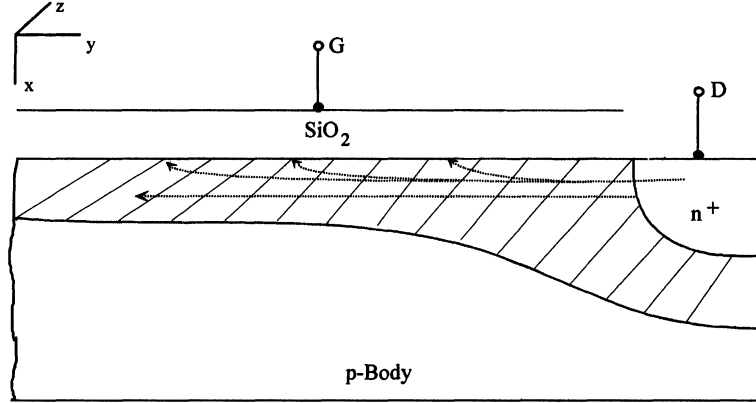
FIGURE 1   Cross sectional view of the body-drain junction of a MOSFET showing current lines.

potential V_D (forward body-drain junction bias, typically 0.2 V) with zero source and body potentials.

The rate of surface recombination [13] for electron or hole, for steady-state conditions, may be written:

$$U_s = \frac{\sigma_{sn}\,\sigma_{sp}\,V_{th}\,N_{st}\,(n_s p_s - n_i^2)}{\sigma_{sn}[n_s + n_i\exp((E_{st} - E_i)/KT)] + \sigma_{sp}[p_s + n_i\exp-((E_{st} - E_i)/KT)]}$$

(2)

where N_{st} is the number of single-level bulk surface recombination centers by unit area, n_s and p_s are the electron and hole densities at the surface, σ_{sn} and σ_{sp} are the capture cross-sections for electrons and holes, respectively, E_{st} is energy level of bulk surface recombination centers, E_i is the semiconductor intrinsic Fermi level, V_{th} is the thermal velocity, n_i is the intrinsic carrier density, T the temperature and K the Boltzmann constant.

The expression of recombination current density may be obtained by integration of the recombination rate U_s over the surface layer. U_s reaches maximum values where the denominator is a minimum [4, 14], which corresponds to the case when $E_{st} = E_i$. Several approximation methods [3–5] make it possible to calculate the recombination current, they consider $E_{st} = E_i$. In order to obtain a complete

theoretical relation between the current and the energy level E_{st} of recombination centers, it is necessary to consider the whole expression of the steady-state recombination rate of the carriers given by Eq. (2).

Furthermore, the study of a gate control diode needs a new approach to these calculations since the gate applied voltage creates a particular potential distribution in the depleted region. Carrier concentrations n_s and p_s in the layer along the interface under the gate are dependent on the surface potential ψ_s and on the drain forward bias V_D [15], they are obtained in the form:

$$n_s = \frac{n_i^2}{N_A} \exp\left[\frac{q}{KT}(\psi_s + V_D)\right] \tag{3}$$

$$p_s = N_A \exp - \left[\frac{q}{KT}\psi_s\right] \tag{4}$$

where N_A is the concentration of shallow dopant in the body.

By integration over the (Si−SiO$_2$) interface, we obtained the contribution of the reverse surface recombination current to the body-drain junction current which introduces in Eq. (1) a reverse surface current I_{02} in the form:

$$I_{02} =$$
$$\frac{qLZ\sigma V_{th} N_{st} n_i^2}{\{(n_i^2/N_A)\exp[(q/KT)(\psi_s + (V_D/2))] + N_A\exp[-(q/KT)(\psi_s + (V_D/2))]}$$
$$\overline{+ n_i\cosh((E_{st} - E_i)/KT)\exp[-(q/KT)(V_D/2)]\}}$$
$$\tag{5}$$

where Z and L are respectively the width and the length of the channel.

I_{02} dependent on energy level of bulk recombination centers, E_{st}, and related to the surface potential ψ_s. The surface potential, ψ_s, is related to the applied gate bias and its variation has been determined (see Appendix I)

3. RESULTS AND DISCUSSION

Figure 2 displays modelling results obtained for the gate controlled body-drain junctions of the MOS structure shown in Figure 1.
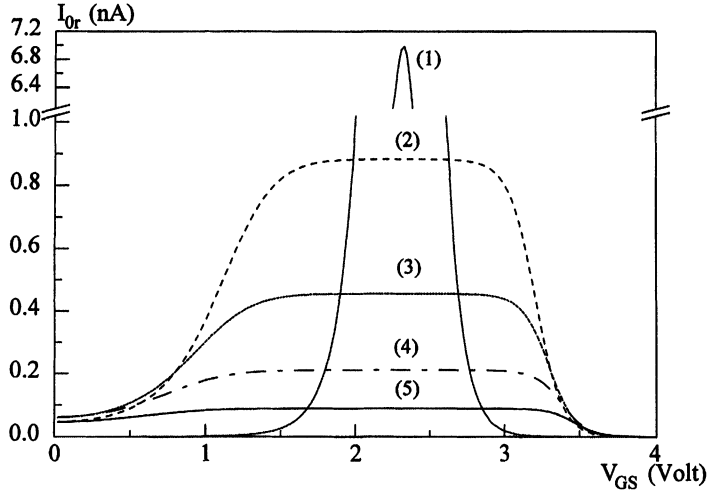
FIGURE 2   Diode surface reverse recombination currents against the gate bias for a different trap energy levels E_{st} refered to Fermi intrinsic level $E_i (L = Z = 10 \mu m$, $V_D = 0.1$ V). 1) $E_{st} - E_i = 0$ eV, $N_{st} = 2.8 \ 10^9$ cm^{-2}; 2) $E_{st} - E_i = 0.23$ eV, $N_{st} = 6.47$ 10^9 cm^{-2}; 3) $E_{st} - E_i = 0.26$ eV, $N_{st} = 9.06 \ 10^9$ cm^{-2}; 4) $E_{st} - E_i = 0.29$ eV, $N_{st} = 1.14$ 10^{10} cm^{-2}; 5) $E_{st} - E_i = 0.31$ eV, $N_{st} = 1.3 \ 10^{10}$ cm^{-2}.

It points out the large influence of the energy level of bulk recombination centers E_{st} compared to the intrinsic Fermi level E_i. For all centers level positions the reverse surface recombination current I_{02} increases as soon as the gate applied bias V_G is raised. A maximum value is reached with subthreshold operating conditions (threshold voltage V_T is close to 3.1 V for this structure) and the reverse current decreases gradually for V_G values close to and then above V_T. Such variations have been previously obtained experimentally [16, 17] from direct measurements of leakage currents and these theoretical results enable us to discuss their physical origin.

The interface recombination center densities (N_{st}) which have been used in this modelling study correspond to the values of interface trap density in a $Si - SiO_2$ system with respective energy levels (E_{st}) described by Sze [15]. The increase in the reverse recombination current I_{02} together with the decrease of $E_{st} - E_i$ reflect that recombination centers located near the center of the energy gap are most active and correspond to a maximum value of the recombination rate U_s given in Eq. (2). As the gate bias increases, a surface potential

appears and the large increase of I_{02} may be attributed to the extension of the junction space charge region within the induced depleted layer under the gate. For gate bias less than, but close to the threshold voltage value a tangential electrical field along the interface appears and drifts the carriers along the interface leading to the observed maximum I_{02} step; for large V_G values the channel is operating, the reverse surface recombination current decreases rapidly and reaches almost a zero value. The electrical field modulates the resistance of the layer under the gate and allows a current to flow in response to the applied drain voltage. This electrical field effect on the surface recombination current is obviously drain bias dependent as shown in Figure (3). The drain bias increases the width of body-drain junction depleted region leading to an increase of I_{02} reverse current.

In order to compare these modelling results with experiments we performed a determination of the I_{02} component from a description of MOSFET body-drain junction characteristics with Eq. (1). In our experiments the transistor is reversed biased and the body-drain diode
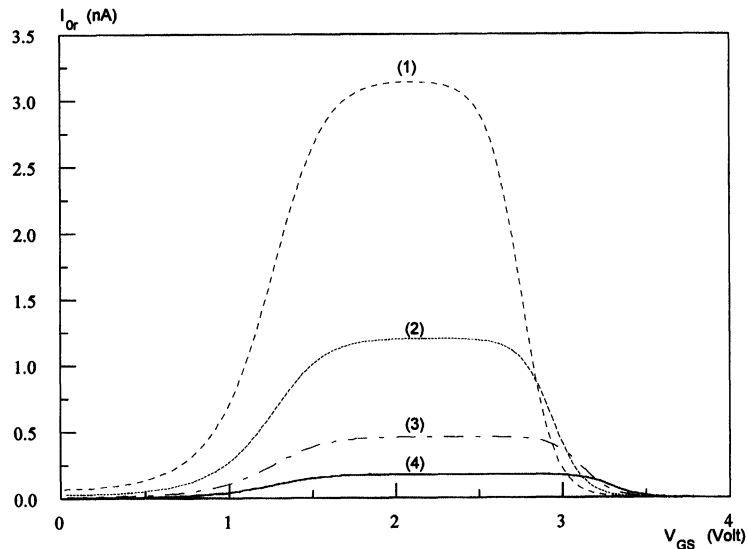

FIGURE 3   Influence of the direct bias of the body-drain junction on the I_{02} diode surface reverse recombination current of a MOSFET ($L = Z = 10\,\mu\text{m}$, $E_{st}-E_i = 0.26\,\text{eV}$, $N_{st} = 9.06\ 10^9\,\text{cm}^{-2}$), 1) $V_D = 0.05\,\text{V}$; 2) $V_D = 0.1\,\text{V}$; 3) $V_D = 0.15\,\text{V}$; 4) $V_D = 0.2\,\text{V}$.

is forward biased, *i.e.*, the body and source potentials are made positive with respect to the drain. A specifically conceived software [11], PARADI, extracts the physical parameters I_{01}, I_{02}, R_s and R_{sh} from the experimental $I(V)$ diode measurements, providing an excellent fit of the characteristic: sets of parameter values are determined for different bias values, using Newton–Raphson method. The selection of the best-descriptive set related to this specific conduction mechanism model (Eq. (1)) is made *via* the calculation of the qualification factor Q, that is the root-mean-square of the distances separating the experimental points from the calculated curve.

Figure (4) displays the agreement between I_{02} computed and experimental values. Theoretical values have been obtained with Eq. (5) and the description makes it possible to determine a surface recombination centers density $N_{st} = 2 \ 10^{10} \, cm^{-2}$; with energy level $E_{st}-E_i = 0.1 \, eV$. Experiments have been performed with drain voltage values lower than 0.2 V in order to assure the validity of the double exponential model (Eq. (1)) description which is confirmed with obtained low Q values. Gate bias values upto 2.5 V have been applied,
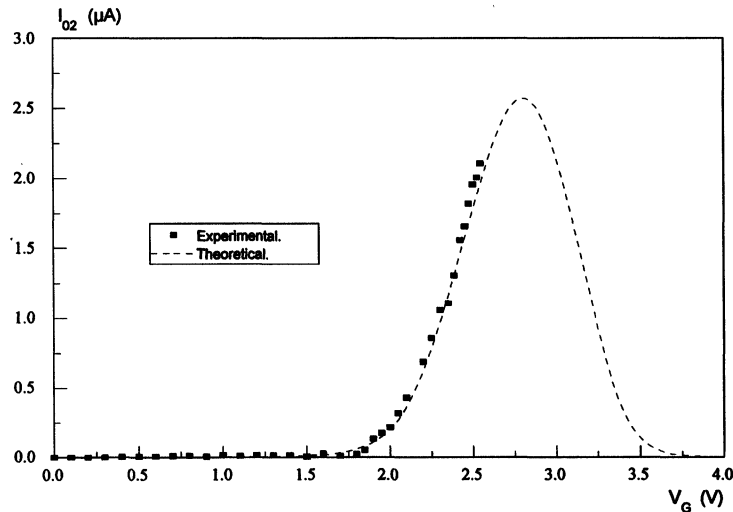

FIGURE 4 Theoretical and experimental surface reverse recombination currents against the gate voltage for the body-drain junction of a MOSFET($L = Z = 10 \, \mu m$, $E_{st}-E_i = 0.1 \, eV$, $V_D = 0.1 \, V$).

since for greater values the $I(V)$ characteristics cannot be described with a diode model, the current being the sum of the direct diode current and of the channel drift current.

4. CONCLUSION

This study of the surface recombination phenomena at the oxide-semiconductor interface of MOSFETs shows the importance of junction recombination current in subthreshold operating conditions. Modelling techniques combined with extraction parameter methods applied to diode structures appear as a powerful tool to investigate the importance of energy level of bulk recombination centers on variation of surface recombination current. The activity of interface traps with energy values in the silicon forbidden bandgap, different from the intrinsic energy Fermi value, have been found to be dependent on the operating conditions. The results presented here are useful for interpretting the effects of energy level and to have a better understanding of M.O.S degradations.

References

[1] Grove, A. S. and Fitzgerald, D. J. (1966). *Solid-State-Electronics*, **9**, 783.
[2] Reddi, V. G. K. (1967). *Solid-State-Electronics*, **10**, 305.
[3] Henry, C. H., Logan, R. A. and Merritt, F. R. (1978). *J. Appl. Phys.*, **49**, 3530.
[4] Sze, S. M. (1985). Semiconductor Devices (Physics and Technology), Wiley, New York.
[5] Hopkinson, C. R., RADECS 93, St-Malo 13–16, 1993, pp. 401–408.
[6] Jang, S. L. (1991). *Solid-State-Electronics*, **34**, 373.
[7] Green, M. A. (1984). *IEEE Trans. On Elect. Dev.*, **ED-31**, 671.
[8] Kosier, S. L., Schrimpf, R. D., Nowlin, R. N., Fleetwood, D. M., Delaus, M., Pease, R. L., Combs, W. E., Wei, A. and Chai, F. (1993). *IEEE Trans. on Nucl. Sc.*, **40**, 1276–1285.
[9] Schrimpf, R. D. (1995). RADECS 95, Arcachon.
[10] Wolf, M. and Ranschenback, H. (1963). *Adv. Energy Convers.*, **3**, 455.
[11] Charles, J. P., Mekkaoui-Alaoui, I., Bordure, G. and Mialhe, P. (1985). *Solid-State-Electronics*, **23**, 807.
[12] Hall, R. N. (1952). *Proc. IRE*, **40**, 1512.
[13] Sah, C. T., Noyce, N. and Schockley, W. (1957). *Proc. IRE*, **45**, 1228.
[14] Nussbaum, A. (1973). *Phys. Stat. Solid*, **19**, 441.
[15] Sze, S. M. (1981). Physics of Semiconductor Devices, Wiley, New York.
[16] Oualid, J., Dugas, J., Jerisian, R., Bouassis, A., Labrunye, D. and Mirabel, J. M. (1991). *J. Phys. III*, **1**, 369.
[17] Sze, S. M. (1967). Physics of Semiconductor Devices, Wiley, New York.

APPENDIX I

Determination of the Surface Potential
at the Oxide-semiconductor Interface

The surface potential ψ_s is related to the gate bias V_G. It may be obtained from the expression of the surface charge density Q_s and from the determination of the oxide capacitance C_{ox} since

$$Q_s = (V_G - \psi_s)C_{ox}. \tag{1}$$

They may be charges generated in the oxide and trapped at the interface, or free charges generated in the depletion region.

Coulomb's law for equilibrium states:

$$Q_s = -\varepsilon_s \left. \frac{d\psi(x)}{dx} \right|_{x=0} \tag{2}$$

where ε_s is the semiconductor permittivity and $\psi(x)$ is the potential at the position x (Fig. 1).

Integrating Poisson's equation, for potential $\psi(x)$, we assume that the surface potential ψ_s is independent of y. The boundary conditions $\psi(x) = \psi_s$ at $x = 0$ gives:

$$\psi(x) = \left[-\sqrt{\frac{qN_A}{2\varepsilon_s}} x + (\psi_s)^{1/2} \right]^2. \tag{3}$$

The surface potential ψ_s is related to the bias V_G and to the potential V_{ox} across the oxide ($\psi_s = V_G - V_{ox}$). Then Eq. (2) gives:

$$Q_s = -(2 \cdot q \cdot \varepsilon_s \cdot N_A)^{1/2} \cdot \psi_s^{1/2}. \tag{4}$$

The oxide capacitance, C_{ox}, is obtained from measurements of the drain potential, V_{DS} in the saturation region:

$$C_{ox} = \frac{[2 \cdot \varepsilon_s \cdot q \cdot N_A (V_{DS} + 2.\psi_B)]^{1/2}}{(V_G - V_{DS} - 2 \cdot \psi_B)} \tag{5}$$

were ψ_B is the potential difference between the Fermi level and the intrinsic level of the bulk semiconductor.

From Eqs. (1), (4) and (5) we obtain an implicit equation which makes it possible to compute the surface potential ψ_s as a function of the gate voltage.