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Simulation of Transport and Noise Properties of SILCs Through Thin-Oxide MOS Structures

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Abstract. We propose a model of stress-induced leakage currents (SILCs) through MOS structures, based on the assumption that SILCs are due to trap-assisted tunneling. Such model allows us to compute transport and noise properties of SILCs, and to show that trap-assisted tunneling can explain the suppression of shot noise in SILCs recently observed in experiments on stressed oxides. We have developed a code based on a self-consistent 1D simulation of transport through a thin MOS capacitor, that allows us to consider an arbitrary distribution of traps in energy and space. Considering the lack of information on the distribution of traps, we show that the simulations provide results in good agreement with the experiments.

Keywords: SILCs, trap-assisted tunneling, MOS structures, shot noise

1. Introduction

Stress Induced Leakage Currents (SILCs) are the excess currents through a thin oxide MOS capacitor observable at low voltages after the structure has been stressed by a large electric field. This effect has been obseved more than twenty years ago (Maserjan and Zamani 1982, Olivo, Nguyen and Riccò 1988), and has been extensively studied from the experimental and theoretical point of view (Moazzami and Hu 1992, Stahis and Maria 1998, Riccò, Gozzi and Lanzoni 1998).

Such a wide interest is due to the fact that SILCs are a major problem for the reliability of MOS structures, and presently constitute the major obstacle to the downscaling of non-volatile memory devices.

Over the years many mechanisms have been proposed for SILCs: tunneling enhancement due to hole trapping (Hemink *et al.* 1996), trap-assisted tunneling (Moazzami and Hu 1992), or an effective reduction of the oxide thickness due to the growth of a conductive filament (Takagi, Yasuda and Toriumi 1999). In recent years, a general consensus is emerging on the predominant role of trap-assisted tunneling. Still lively debated are the issues of whether tunneling is due to electrons from the valence band or the conduction band (Riccò, Gozzi and Lanzoni 1998) and whether tunneling is elastic or inelastic (Takagi, Yasuda and Toriumi 1999).

The presence of electron traps in the insulator can lead to an intolerable increase of the leakage current, since trap-assisted tunneling can take place, i.e., electrons can tunnel through the dielectric in a two-step process, first from one electrode to the trap, and then from the trap to the other electrode.

In particular, the observed non-repeatability of the I–V characteristics of a device structure consisting of a dielectric layer stacked between two electrodes is often due to the presence of traps induced in the dielectric by a large applied electric field. Such traps degrade the insulating properties of the dielectric and lead to an increase of the leakage current by a few orders of magnitude.

It is therefore very important to fully understand transport in the trap-assisted tunneling regime. In this paper, we present a model for DC properties and noise through an insulating layer in which traps are present with a known distribution in volume and energy. Noise, in particular, can provide deep insights into the transport mechanisms of such devices, since, as is well known, it is extremely sensitive to the presence of defects.

2. Model

For the sake of generality, let us consider the semiconductor-insulator-semiconductor structure whose conduction and valence bands are sketched in Fig. 1. In the case of metal contacts the situation is simpler, since only one band per electrode can be considered. In addition, let us consider a trap in the oxide, consisting in a localized electron state at position x' in the oxide ($0 < x' < d$) and at energy E_α. We will assume that the trap has a single level with two possible states (spin up and down), but Coulomb repulsion prevents two electrons from occupying the same trap. We follow the notation used in the case of generation-recombination processes (Iannaccone, Macucci and Pellegrini 1997): we call "generation" rate the transition rate from an electrode to the unoccupied trap, and "recombination" rate the transition rate from the occupied trap to one electrode. As can be seen in Fig. 1, we consider four different generation rates, on the basis of the location of the initial state: generation rate from the conduction band of electrode 1 (g_{1c}), from the valence band of electrode 1 (g_{1v}), from the conduction band of electrode 2 (g_{2c}) from the valence band of electrode 2 (g_{2v}). Analogously, we define the four recombination rates, on the basis of the location of the final state (the same subscript notation is used). Let us call $|\alpha\rangle$ the electron state in the trap, and let us consider a state $|\beta\rangle$ in the conduction band of region 1. According to the Fermi "golden rule" the transition rate from $|\beta >$ to $|\alpha\rangle$ would be

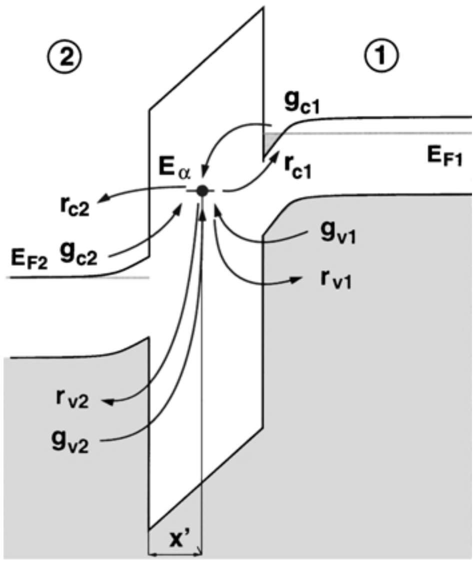

Figure 1. Band profile of a semiconductor-insulator-semiconductor structure, with a trap of energy E_α at depth x' and sketch of the eight transition rates considered.

$$\nu_{\beta\to\alpha} = \frac{2\pi}{\hbar}|M(\alpha,\beta)|^2 h_\Gamma(E_\alpha - E_\beta) \qquad (1)$$

where $\hbar$ is the reduced Planck constant, $M(\alpha,\beta)$ is the transition matrix element between state $|\alpha\rangle$ and $|\beta\rangle$, E_α and E_β are the energies of states $|\alpha\rangle$ and $|\beta\rangle$, respectively. The function h_Γ is a lorentian curve of halfwidth Γ,

$$h_\Gamma(E_\alpha - E_\beta) = \frac{\Gamma/\pi}{(E_\alpha - E_\beta)^2 + \Gamma^2}, \qquad (2)$$

and represents the simplest way to account for inelastic transitions. As can be noticed, h_Γ tends to a delta function as Γ approaches 0, i.e., when only elastic transitions are considered. The larger Γ, the larger degree of inelastic transitions allowed.

The transition rate can also be related to the probability current density $J(\beta, x')$ of state $|\beta\rangle$ on the plane x' where the trap is located through the so-called capture cross section $\sigma_{\alpha,\beta}$

$$\nu_{\beta\to\alpha} = \sigma_{\alpha,\beta} J(\beta, x') = \sigma_{\alpha,\beta} T_1(E_l)\nu_1(E_l) \qquad (3)$$

where E_l is the energy in the x direction of state $|\beta\rangle$, $T_1(E_l)$ is the transmission probability of the one-dimensional barrier from x' to d, and ν_1 is the so-called attempt frequency of the state of longitudinal energy E_l. The trap cross section can depend of course on the trap state and on the initial state in a non trivial way. However, given our lack of knowledge on the nature of traps, we make the simplest assumption that agrees with Eq. (1): $\sigma_{\alpha,\beta} = kh_\Gamma(E_\alpha - E_\beta)$, where k is a constant.

The state $|\beta\rangle$ is defined by its longitudinal energy E_l, its energy in the transverse plane $E_T (E_\beta = E_l + E_T)$ and its spin. The generation rate g_{1c} is obtained by integrating (3) over all occupied states in the conduction band of electrode 1, while r_{1c} is obtained by integrating (3) over all unoccupied states. The details of the calculations are discussed in detail elsewhere (Iannaccone unpublished). The other transition rates can be straightforwardly derived. We can group transition rates as follows:

$$g_1 = g_{1c} + g_{1v}; \quad r_1 = r_{1c} + r_{1v}$$
$$g_2 = g_{2c} + g_{2v}; \quad r_2 = r_{2c} + r_{2v} \tag{4}$$

The average current I' through the trap can therefore be written as (Iannaccone unpublished)

$$I' = qr_2 \frac{g_1 + g_2}{g_1 + g_2 + r_1 + r_2}, \tag{5}$$

while the noise spectral density of the noise current at zero frequency is readily obtained with a procedure very close to that used for obtaining generation-recombination noise and noise in resonant tunneling structures (Iannaccone, Macucci and Pellegrini 1997) that is discussed in detail elsewhere (Iannaccone unpublished):

$$S' = 2qI'\left(1 - \frac{g_1 r_2}{(g_1 + r_1 + g_2 + r_2)^2}\right) = 2q\gamma' I'. \tag{6}$$

The shot noise suppression factor γ', or Fano factor, is defined as $\gamma' = S'/2qI'$: as can be seen from (6), is between 0.5 and 1 (Iannaccone, Macucci and Pellegrini 1997).

Let us assume that traps are distributed with a density η per unit volume per unit energy. The total trap-assisted current density J_{TAT} and the associated noise spectral density S_{TAT} can be obtained by integrating I' and S' over E_α in the insulator gap, and x', in the longitudinal direction from 0 to d, i.e.

$$J_{\mathrm{TAT}} = \iint I' \eta(E_\alpha, x') dE_\alpha \, dx',$$
$$S_{\mathrm{TAT}} = \iint S' \eta(E_\alpha, x') dE_\alpha \, dx'. \tag{7}$$

J_{TAT} is proportional to the product of the capture cross section and the trap density, while the Fano factor

$$\gamma_{\mathrm{TAT}} \equiv \frac{S_{\mathrm{TAT}}}{2q J_{\mathrm{TAT}}} = \frac{\iint \gamma' I' dx' dE_\alpha}{\iint I' dx' dE_\alpha}, \tag{8}$$

is again between 0.5 and 1, and is independent from any constant factor in (7).

3. Numerical Results and Discussion

We have performed a numerical simulation of the model for trap-assisted-tunneling just described: first, we solved the non-linear Poisson equation in order to obtain the electron density and the band profiles; then, we computed the tunneling current density and the trap-assisted current density for an arbitrary value of $k\eta$. We have considered MOS capacitors realized on (100) oriented n silicon substrates phosphor doping 5×10^{15} cm^{-3}. The oxide thickness is 6 nm and the top gate is made of polysilicon with donor doping 10^{20} cm^{-3}.

Figure 2 shows the I–V characteristic for a fresh oxide (with no traps), and for increasing values of $k\eta$ in steps of one decade. We considered a uniform trap density with a constant value between 1 eV and 3 eV below the oxide conduction band, and $\Gamma = 10$ meV. Results exhibit good qualitative agreement with the experimental measurement (Olivo, Nguyen and Riccò 1988, Moazzami and Hu 1992, Takagi, Yasuda and Toriumi 1999, Iannaccone *et al.* 2000).

However, the details of the trap density have a strong influence on the DC properties and on noise in trap-assisted-tunneling. For example, in Fig. 3 we plot the I–V characteristic obtained with three different energy distributions of η. The thick solid curve is the current in the fresh oxide, while the other curves are obtained assuming a uniform η between E^* and 3 eV below the oxide conduction band, where $E^* = 0$ V for the thin solid line, $E^* = 1$ eV for the dotted line, $E^* = 2$ V for the dashed line. It can be clearly seen that

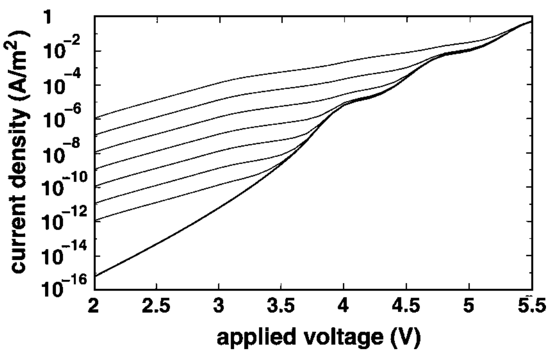

Figure 2. Computed current density as a function of the applied voltage for a fresh oxide with thickness of 6 nm (thick line) and for increasing values of $k\eta$ in steps of one decade (thin lines). We considered a uniform trap density with a constant value between 1 eV and 3 eV below the oxide conduction band, and a value of $\Gamma = 10$ meV.

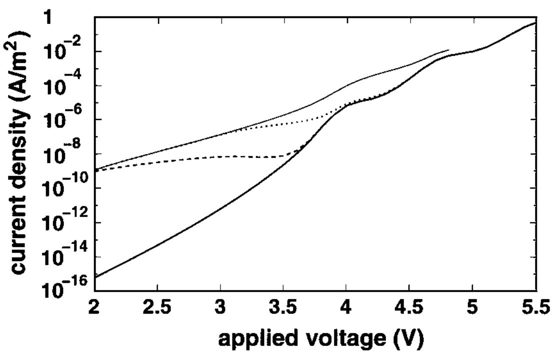

Figure 3. Computed current density as a function of the applied voltage for a fresh oxide with thickness of 6 nm (thick solid line) and for a uniform trap density with a constant value between E^* and 3 eV below the oxide conduction band, where $E^* = 0$ V (thin solid line), 1 eV (dotted line), and 2 V (dashed line).

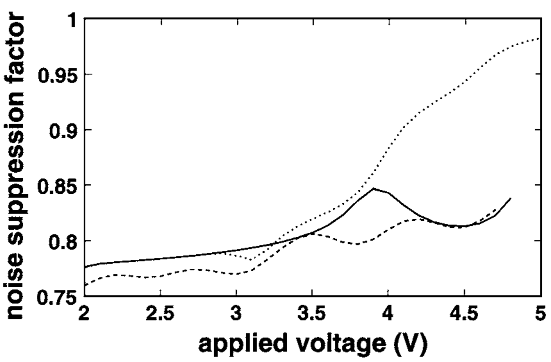

Figure 4. Computed noise suppression factor as a function of the applied voltage for a fresh oxide with thickness of 6 nm (thick solid line) and for a uniform trap density with a constant value between E^* and 3 eV below the oxide conduction band, where $E^* = 0$ V (thin solid line), 1 eV (dotted line), and 2 V (dashed line).

higher energy traps participate to transport at larger gate voltage.

For the same cases, we plot in Fig. 4 the shot noise suppression factor γ. As expected, it is in the range 0.5–1, pretty close to 0.8, and in good agreement with the few experimental results available (Iannaccone *et al.* 2000, Crupi *et al.* 2001). The large differences among the noise suppression factor in the three cases considered need to be studied systematically, by considering the contribution of each energy bin. Maximum suppression of shot noise ($\gamma = 0.5$) and maximum current through the trap is obtained when g_1 and r_2 are equal while other transistion rates are negligible. Away from this condition, γ quickly approaches one and the current decreases. For this reason, a slight variation of trap density in energy can have a significant effect on γ.

In conclusion, our simple model allows to compute the DC and noise properties of trap-assisted-tunneling current and to obtain good agreement with experiments, considering the poor information available on the detailed distribution of traps. Proper refinement of the model requires accurate information on capture cross section of traps, and on trap density.

Acknowledgments

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