Theory and Experiment of Suppressed Shot Noise in Stress-Induced Leakage Currents

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Theory and Experiment of Suppressed Shot Noise In Stress-Induced Leakage Currents

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***Abstract*—In this paper, we present a theoretical and experimental investigation of shot noise in metal-oxide-semiconductor (MOS) capacitors. We show that stress-induced leakage currents exhibit suppressed shot noise with respect to the "full" power-spectral density $S = 2qI$ associated to a purely Poissonian process, which is measured in the tunneling current through a fresh oxide. Experimental results on MOS capacitors with 6 and 10 nm oxides are presented. We present a model of stress-induced leakage currents (SILCs) based on trap-assisted tunneling that takes into account elastic and inelastic transitions, and is able to reproduce the relevant physics. Numerical simulations based on the proposed model are presented and exhibit good agreement with the experiments, given the lack of information on the nature of traps.**

***Index Terms*—Leakage currents, MOS devices, semiconductor device reliability, shot noise, tunneling.**

I. Introduction

Stress-induced leakage currents (SILCs) are the excess currents through a thin-oxide metal-oxide-semiconductor (MOS) capacitor observable at low voltages after the structure has been stressed by a large electric field. This effect has been observed more than years ago [1], [2] and has been extensively studied from the experimental and theoretical point of view [3]–[5].

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 nonvolatile memory devices.

Among the transport mechanisms proposed to explain SILCs (tunneling enhancement due to hole trapping [6], trap-assisted tunneling [3], an effective reduction of the oxide thickness due to the growth of a conductive filament [7]) trap-assisted tunneling is presently considered as the most likely. The nature of traps and of the type of tunneling (elastic or inelastic) is not yet clear [7], [9].

In recent years, shot noise has been widely recognized as an important source of information on the transport mechanisms in mesoscopic and nanoscale devices and of electron-electron interaction [10]–[13]. In addition, researchers in the field of semiconductor devices have known for a long time that noise—in particular $1/f$ noise and generation-recombination noise—is extremely sensitive to the presence of defects. Therefore, in devices where transport is essentially based on defects, noise provides useful insights of conduction mechanisms.

A recent letter shows that shot noise can be used as a probe of the transport mechanism of SILCs in MOS structures [14]. In particular, the power spectral density of shot noise associated to the current through MOS capacitors is reduced in stressed oxides with respect to fresh oxides.

In this paper, we extend significantly those preliminary results, as far as both theory and experiments are concerned: We present a complete model for current and noise through thin-oxide MOS capacitors based on elastic and inelastic trap assisted tunneling, and a broader range of experimental results. By comparing the experimental results with simulations based on our model, we can show that, even if the nature of traps is not completely clear, our model is able to capture all the relevant physics.

The paper is organized as follows: In Section II we describe our model of noise and transport in the SILC regime, based on trap-assisted-tunneling and the possibility of inelastic transitions, where Pauli exclusion and Coulomb repulsion acting on each trap lead to suppressed shot noise. We also show that such a suppression could not occur if hole trapping or the conductive filament were responsible for the stress-induced leakage currents. In Section III we present experimental results on MOS capacitors with 6- and 10-nm-thick oxide, exhibiting suppressed shot noise in the SILC regime between 63 and 83% of the full shot level. In Section IV we show the results of simulations on the experimental structures and in Section V we present our conclusions.

II. Model

The tunneling current I_{fresh} through a perfect oxide layer consists of several events per unit time, each corresponding to the transfer of an electron charge $-q$ from the cathode to the anode as a consequence of a tunneling event. In this case, the electrons behave as independent particles, and the tunneling probability is only a function of the electron energy, barrier thickness and shape, and the density of states. The tunneling current is therefore the result of a Poissonian process, and the power spectral density of the current noise S is therefore given by the known expression for "full" shot noise $S = 2qI_{\mathrm{fresh}}$ [15].

After electric field stress, the well-known phenomenon of SILCs can be observed: The current, especially at low fields,

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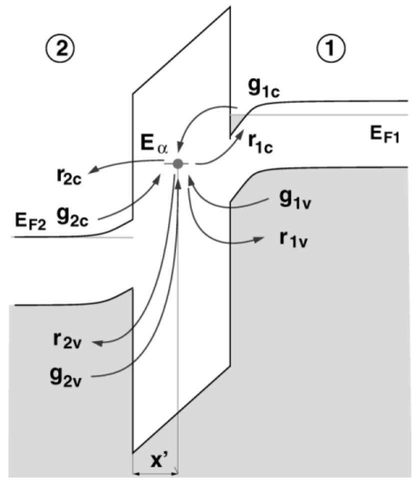

Fig. 1. Band profile of a MOS structure with possible transitions from the contacts to a trap in the oxide of energy E_α and vice versa. Region 1 is the substrate, region 2 is the polysilicon gate.

increases by orders of magnitude, meaning that some additional transport mechanisms becomes dominant. Over the years, several microscopic mechanisms have been proposed. Most of them would still allow electrons to behave independently, and therefore would correspond to a "full" shot-noise spectrum. Indeed, the localized thinning of the oxide due to the presence of a conductive filament [7], the localized lowering of the oxide barrier, and the local alteration of the oxide barrier due to hole trapping [6], would only increase the tunneling probability for electrons in the neighborhood of the defect, but electrons could still be treated as independent particles not interacting with each other, so that the tunneling current would again be governed by Poisson statistics.

On the other hand, the noise properties of SILCs are significantly altered if we ascribe such currents to trap-assisted-tunneling, a two-step process in which electrons first tunnel from the cathode to a trap in the oxide, then from the trap to the anode. Because of Coulomb repulsion and Pauli exclusion principle, only one electron at a time can occupy the same trap; this means that the probability for an electron to undergo a two-step tunneling process through a given trap depends on whether that trap is currently occupied or not. This specific aspect introduces correlation between electrons using the same trap for tunneling; therefore, the current is no more a sum of independent tunneling events, and the process is non– Poissonian (in fact, sub-Poissonian, i.e., with a reduced variance).

In the rest of the section, we present a model for dc and noise properties of SILCs based on trap-assisted-tunneling. 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 of 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 [16] and [17]: 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 $|\beta\rangle$ to $|\alpha\rangle$ would be

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

where $\hbar$ is the reduced Planck's 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

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

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 is 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 $\sigma_{\alpha,\beta}$

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

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 (1-D) 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 state $|\beta\rangle$ in a nontrivial way. However, given our lack of knowledge on the nature of traps, we make the simplest assumption that is consistent with (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

$$g_{1c} = 2\int_{E_{c1}}^{\infty} dE_l \int_0^{\infty} dE_T k h_\Gamma(E_l + E_T - E_\alpha) \times T_l(E_l)\nu_1(E_l) f_1(E_l + E_T)\rho_1(E_l)\rho_T. \tag{4}$$

The factor 2 takes into account spin conservation, ρ_1 and ρ_T are the densities of states in the longitudinal direction and in the transversal plane, respectively, $f_1(E_l + E_T)$, and E_{c1} are the Fermi–Dirac occupation factor and the conduction band edge in the first electrode, respectively.

The recombination rate r_{1c} has an expression very similar to (4), with the difference that the integral has to be performed over unoccupied states in the conduction band of electrode 1 with the same spin of the trapped electron

$$r_{1c} = \int_{E_{c1}}^{\infty} dE_l \int_0^{\infty} dE_T k h_\Gamma(E_l + E_T - E_\alpha) \times T_l(E_l)\nu_1(E_l)\left[1 - f_1(E_l + E_T)\right]\rho_1(E_l)\rho_T. \quad (5)$$

At this point, the expressions of the other transition rates can be derived more straightforwardly, and we will not write them in detail. We can group transition rates as follows

$$\begin{aligned} g_1 &\equiv g_{1c} + g_{1v}; \quad r_1 \equiv r_{1c} + r_{1v} \\ g_2 &\equiv g_{2c} + g_{2v}; \quad r_2 \equiv r_{2c} + r_{2v}. \end{aligned} \quad (6)$$

The occupation factor f' of the trap in the steady-state regime can be readily obtained by imposing the detailed balance of generation and recombination

$$f' = \frac{g_1 + g_2}{g_1 + g_2 + r_1 + r_2}. \quad (7)$$

The average current I' through the trap can therefore be written as

$$I' = qg_1(1 - f') - qr_1 f' = qr_2 f', \quad (8)$$

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, [17], that will be discussed in detail elsewhere [18]

$$S' = 2qI'\left[1 - \frac{g_1 r_2}{(g_1 + r_1 + g_2 + r_2)^2}\right] = 2q\gamma' I'. \quad (9)$$

The shot noise suppression factor γ', or Fano factor, is defined as $\gamma' = S'/2qI'$: As can be seen from (9), this is between 0.5 and 1 [17].

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.,

$$\begin{aligned} J_{\mathrm{TAT}} &= \iint I'\eta(E_\alpha, x')\, dE_\alpha\, dx' \\ S_{\mathrm{TAT}} &= \iint S'\eta(E_\alpha, x')\, dE_\alpha\, dx'. \end{aligned} \quad (10)$$

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

$$\gamma_{\mathrm{TAT}} \equiv \frac{S_{\mathrm{TAT}}}{2qJ_{\mathrm{TAT}}} = \frac{\iint \gamma' I'\eta(E_\alpha, x')\, dx'\, dE_\alpha}{\iint I'\eta(E_\alpha, x')\, dx'\, dE_\alpha} \quad (11)$$

is again between 0.5 and 1, and is independent from any constant factor in (4) and (10).

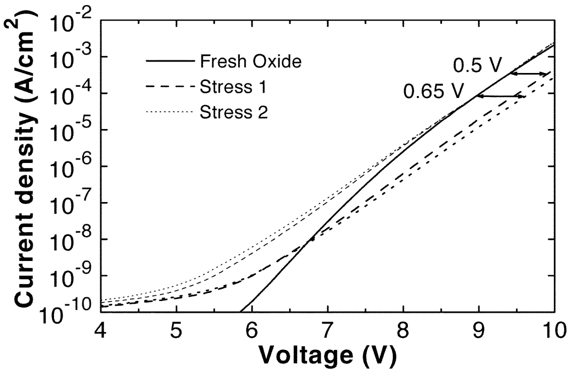

Fig. 2. *I–V* curves of the MOS structure with the 10-nm-thick oxide for the fresh oxide (solid line), after 10 s of FN stress at 12.8 V (dashed line), and after 15 s of FN stress at 12.8 V (dotted line).

III. Experiments

The samples considered in this study are MOS capacitors realized on (100) oriented n^+ silicon substrates with an n^- epitaxy (phosphor 5×10^{15} cm^{-3}). Gate oxides with two different thicknesses, 6 and 10 nm, and an active area of 1.225 $\times 10^{-3}$ cm^2, were grown in O_2 atmosphere. A 300-nm-thick polycrystalline silicon layer was grown at 620 °C by low—pressure chemical vapor deposition (LPCVD), and successively n^+ doped by using a chemical diffusion source of $POCl_3$. An Al : Si alloy metal layer of 1.2 mm thickness was then grown onto the polycrystalline silicon gate. Finally the devices were packaged in metal frames. The experiments have been realized at room temperature using a dedicated, PC-based low noise measurement system.

First, we measured the *I–V* characteristics and the noise power spectral density of the current through the fresh oxide for several values of the dc current. Successively, we stressed the MOS capacitors for a few seconds with a gate voltage of 7.8 V (8 V is the breakdown voltage of such oxides) for the 6-nm-thick oxide and of 12.8 V for the 10-nm-thick oxide. Then, we measured again the *I–V* characteristics and the current noise power spectral density at the same dc current levels considered before stress. Measurements were performed with a constant voltage source, but we checked that the variation of the level of the dc current during a single measurement was smaller than 1% of the corresponding mean value. In order to obtain an almost steady-state current in the SILC regime, the measurements have been realized after the initial period, characterized by a current decay due to the trap-filling process [3].

A. Results for the 10-nm-Thick Oxide

First, we describe the experimental results for the 10-nm-thick oxide. In Fig. 2 we have plotted the measured current density J as a function of the gate voltage for the MOS capacitor before stress (thick solid line), after 10 s at 12.8 V (stress 1—thick dashed line), and after 15 s stress at 12.8 V (stress 2—thin dotted line). Negative charge is trapped in the oxide during stress, causing a voltage shift of $V_{\mathrm{shift1}} = 0.5$ V after stress 1 and $V_{\mathrm{shift2}} = 0.65$ V after stress 2. These values can be simply obtained as the quantity by which the *J–V* characteristics after stress must be shifted along the V-axis in

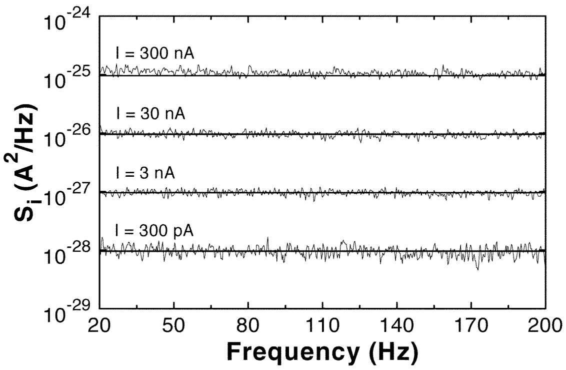

Fig. 3. Power-spectral density of the noise current S_i for four different values of the dc current through the 10-nm-thick oxide. Straight lines fitting each curve represent the full shot-noise level $S_{\mathrm{full}} = 2qI$.

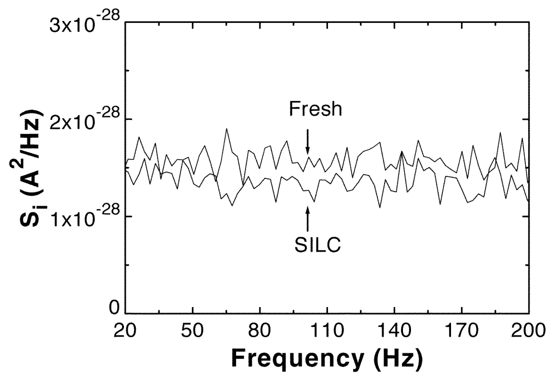

Fig. 4. Power spectral density of the noise current through the 10 nm oxide before and after voltage stress.

order to overlap with the J–V curve of the fresh oxide at large voltages. The stressed J–V curves after shift are also plotted in

The total current after stress J can be decomposed in a component not assisted by traps, which corresponds to the one before stress I_{fresh} and a component due to SILCs I_{SILC}, which can be written as

$$I_{\mathrm{SILC}}(V) = I(V + V_{\mathrm{shift}}) - I_{\mathrm{fresh}}(V). \tag{12}$$

In Fig. 3 we plot the power-spectral density of the noise current S_i before stress for four operating points in a range of four decades of the dc current. At frequencies higher than a few Hertz, the power-spectral density of the noise current S_i exhibits a plateau, which is perfectly fitted by the straight line corresponding to $S_{\mathrm{full}} = 2qI_{\mathrm{fresh}}$, also plotted in the figure.

After stress, the noise power-spectral density still exhibits a plateau, but at a reduced level, as shown in Fig. 4. For stressed oxides, we have measured S_i in a range of dc currents for which the background noise of the instrumentation can be discarded and the SILC component is a relevant fraction of the total current.

We assume that the "direct" tunneling component (in the sense of not assisted by traps) I_{fresh}, and the SILC component I_{SILC} are uncorrelated, i.e., that, apart from the shift in the J–V curve, trapped electrons have a negligible effect on "direct" tunneling electrons. Then, we can write the total spectrum as

$$S_i = \gamma 2qI = 2qI_{\mathrm{fresh}} + \gamma_{\mathrm{SILC}} 2qI_{\mathrm{SILC}}, \tag{13}$$

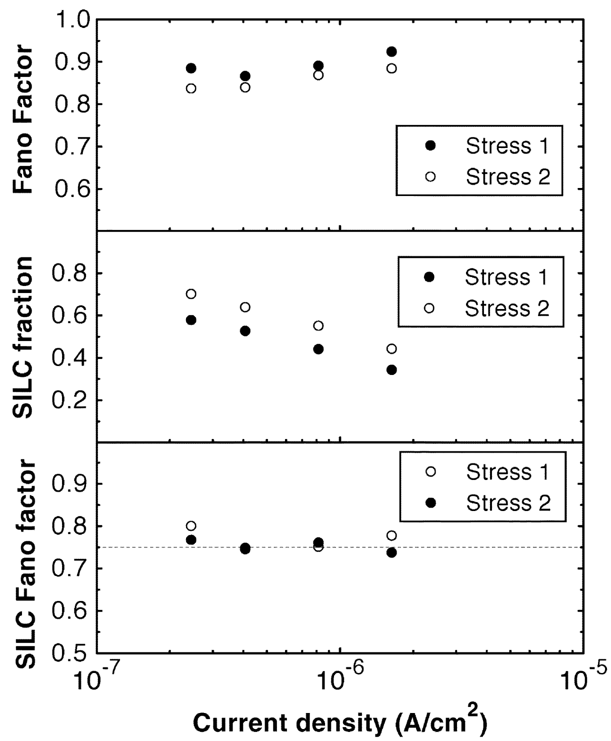

Fig. 5. Fano factor, SILC fraction and SILC Fano factor as a function of the total current density for the 10 nm oxide after stress.

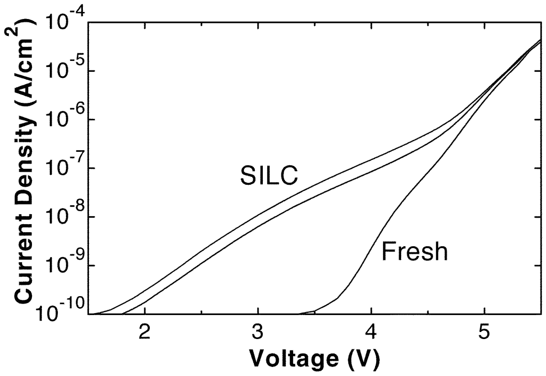

Fig. 6. I–V curves of fresh oxide and after two different periods of FN stress for the MOS structure with 6 nm-thick oxide. The n-MOS was biased in the accumulation region.

where γ and γ_{SILC} are the suppression factor of the total current and of the SILC component, while the "direct" tunneling component exhibits full shot noise, as shown in Fig. 3. I, S_i, and γ are known from measurements on the stressed MOS structures, I_{fresh} is assumed to be equal to the current measured before stress for a gate voltage reduced by the corresponding V_{shift} and γ_{SILC} is obtained from (13).

In Fig. 5 the Fano factor γ, the SILC fraction I_{SILC}/I, and the SILC Fano factor γ_{SILC} are plotted as a function of the total current density after stress 1 and stress 2. In the considered current range, γ_{SILC} is close to 0.75, and is practically independent of the duration of stress.

B. Results for 6 nm-Thick Oxides

Fig. 6 shows the typical J–V characteristics measured before and after stress in the Fowler–Nordheim (FN) regime for the MOS capacitor with the 6 nm oxide. For this thinner oxide, there

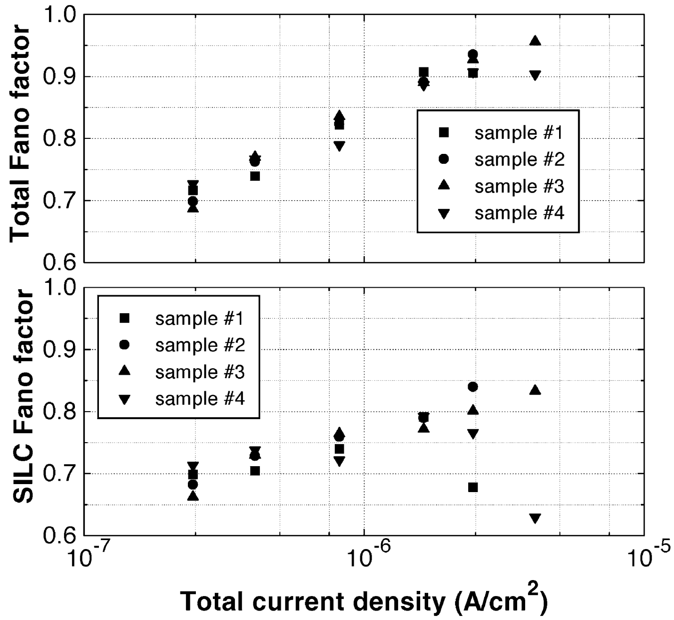

Fig. 7. Fano factor of total current γ (top) and of the SILC component γ_{SILC} (bottom) for four samples of stressed oxide as a function of the total dc current level. Sample 4 is the one whose dc characteristics are plotted in Fig. 6.

is no charge trapping during stress, and the I–V characteristics before and after stress completely overlap at large voltages.

In Fig. 7 γ and γ_{SILC} are plotted as a function of the total current I for four different samples; γ_{SILC} is found to be between 0.63 and 0.83 in all the considered dc current range, while γ approaches 1 at large currents, when the contribution of SILCs is negligible. As can be seen, results are well reproducible (within 10%) at smaller currents, where SILCs are predominant and γ_{SILC} can be extracted with a small relative error.

IV. Numerical Results and Discussion

We have performed numerical simulations of the I–V characteristics of the 6 and 10 nm MOS capacitors on which the experiments have been performed, based on the model described in Section II. First, we solved self-consistently the Poisson–Schrödinger 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 a chosen value of $k\eta$. We have assumed a polysilicon donor doping of 10^{20} cm^{-3}.

Obtaining a quantitative agreement between simulations and experiments is beyond the scope of the present paper since there are two important parameters that are not known with sufficient accuracy: First, the oxide thickness is obtained from ellipsometry, and an error of only 0.5 nm on the oxide thickness causes an error of about two orders of magnitude in the tunneling current. In addition, there is no consensus on the energy distribution of traps: for example, some authors have estimated an energy, measured from the oxide conduction band, of -1.2–1.8 eV [7] or of -2.42 eV [9]. In addition, some measurements predict a fixed energy loss of 1.5 eV in the trap [7], while other suggest that tunneling is practically elastic.

Given this lack of information, we follow a simpler approach and consider a trap density uniform in volume and in energy over a wide energy range (of the order of eVs). In addition, we do not assume a fixed energy loss in the trap but only allow for inelastic transitions as explained in Section II. Nevertheless, we expect that if our model is able to capture the significant transport mechanisms in stressed oxides, our simulation should be able to reproduce at least qualitatively the dc and noise properties of the structures.

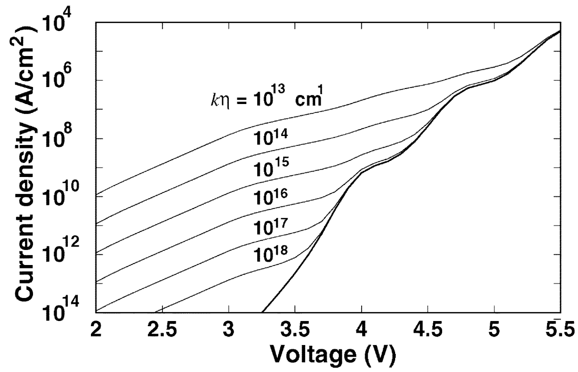

Fig. 8. Computed current density as a function of the applied voltage for a fresh oxide with thickness of 6 nm (thick line) and for increasing values of $k\eta$ in steps of one decade (thin lines). We considered a uniform trap density with a constant value between 1 and 3 eV below the oxide conduction band, and a value of $\Gamma = 10$ meV.

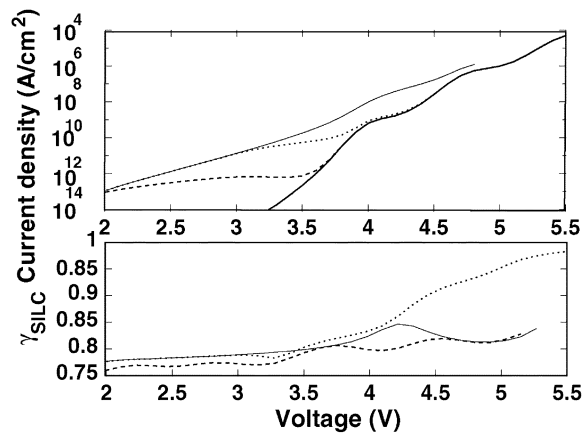

Fig. 9. Computed current density (above) and suppression factor (below) as a function of the applied voltage for a fresh oxide with thickness of 6 nm (thick solid line) and for a uniform trap density with a constant value between E^* and 3 eV below the oxide conduction band, where $E^* = 0$ V (thin solid line), 1 eV (dotted line), and 2 V (dashed line).

Fig. 8 shows the computed J–V characteristics for a 6-nm oxide in fresh conditions (thick solid line), and after stress with increasing values of $k\eta$ in steps of one decade. We considered a uniform trap density with a constant value between 1 and 3 eV below the oxide conduction band, and $\Gamma = 10$ meV. As can be seen, results exhibit good qualitative and reasonable quantitative agreement with the measurements plotted in Fig. 6.

However, the details of the trap density have a strong influence on the dc properties and of noise in trap-assisted-tunneling. For example, in Fig. 9 we plot the I–V characteristics obtained with three different energy distributions of η. The thick solid curve is the current of the fresh oxide, while the other curves are obtained assuming a uniform η between a certain energy E^* and 3 eV below the oxide conduction band, where we consider $E^* = 0$ V for the thin solid line, $E^* = 1$ eV for the dotted line,

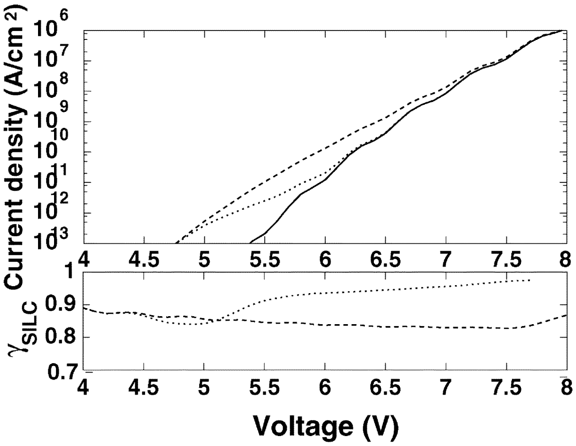

Fig. 10. Computed current density (above) and suppression factor (below) as a function of the applied voltage for a fresh oxide with thickness of 10 nm (thick solid line) and for a uniform trap density with a constant value between E^* and 3 eV below the oxide conduction band, where $E^* = 1$ V (dotted line), and 2 V (dashed line).

and $E^* = 2$ V for the dashed line. It can be clearly seen that higher energy traps participate to transport at larger gate voltage. We have also plotted in the same figure the corresponding shot noise suppression factor γ_{SILC}. As expected, it is in the range 0.5–1, pretty close to 0.8, again, in reasonable agreement with the experimental results of Fig. 7.

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 interval. 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 transition 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.

The computed *I–V* curves and γ_{SILC} for the 10-nm oxide are shown in Fig. 10. The considered trap energy ranges are between 0 and 3 eV, and between 1 and 3 eV below the oxide conduction band (traps in the energy range between 2 and 3 eV carry a negligible current). The SILC Fano factor is not less than 0.8, i.e., slightly larger than the experimental value of 0.75. Again, given the lack of information of the energy of trap, we consider that the agreement between experiments and simulations is satisfactory. Let us also highlight the fact that our model slightly underestimates the negative correlation between electron crossings, because it completely discards Coulomb interaction between different traps, and therefore slightly underestimates the suppression of shot noise.

V. Conclusion

We have characterized, with experiments and simulations, the dc and noise properties of MOS capacitors subjected to voltage stress. The main focus of this paper has been on the suppression of shot noise in the stress-induced leakage current. We have presented experimental results on two different oxide thicknesses, and a model capable of capturing the relevant physics. We have shown that even with incomplete information on the nature of traps we are able to obtain numerical results in reasonable agreement with the experiment.

The experiments and the model allow us to conclude that the observed shot-noise suppression is a further indication that trap-assisted tunneling is responsible for SILCs. Indeed, the alternative proposed mechanisms based on hole trapping or on the presence of a conductive filament would not introduce any correlation among electrons, and therefore would be in contrast with the observed noise suppression. Finally, let us point out that the conductance of stressed capacitors is more than four orders of magnitude smaller than the conductance quantum; therefore, shot-noise suppression cannot be associated to the quantization of conductance.

This paper also supports our belief in the importance of noise as a tool for gaining insights into the transport mechanisms. We believe that additional information on the distribution and nature of traps can be obtained by comparing the theoretical dc and noise properties due to a candidate distribution of traps with the measurements. We are presently working in that direction.

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