Suppressed shot noise in trap-assisted tunneling of metal–oxide–semiconductor capacitors

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Suppressed shot noise in trap-assisted tunneling of metal–oxide–semiconductor capacitors

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We show that the tunneling current of a metal–oxide–semiconductor capacitor subjected to voltage stress exhibits suppressed shot noise with respect to the ''full'' shot noise level associated with the same current before stress. We provide experimental results exhibiting a suppression down to about 70% and a theoretical model for transport and noise in the stress induced leakage current regime based on trap assisted tunneling, which is able to reproduce such reduction. Numerical results from the model are compared with measurements.
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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.[1,2] In this letter we show, with theory and experiments, how shot noise can be used as a probe of the transport mechanism of stress-induced leakage currents (SILCs), the excess currents through thin-oxide metal–oxide–semiconductor (MOS) structures observable at low voltages after the structure has been stressed by a high electric field.[3]

Over the years many mechanisms have been proposed for SILCs: tunneling enhancement due to hole trapping,[4] trap-assisted tunneling,[5,6] or an effective reduction of the oxide thickness due to the growth of a conductive filament.[7] 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,[8] and whether tunneling is elastic or inelastic.[7]

First, we describe a model for noise and transport in the SILC regime based on trap-assisted tunneling, and show that 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 SILC currents. Furthermore, we present experimental results exhibiting suppressed shot noise in the SILC regime down to about 70% of the full shot level, and compare the direct current (dc) and noise characteristics with numerical simulations based on the proposed model.

Let us consider the conduction and valence bands of a MOS structure as sketched in the inset of Fig. 1, and let us consider a trap in the oxide, consisting in a localized electron state at depth x' in the oxide $(0<x'<d)$ and at energy E'. As it is well known, shot noise is suppressed if some negative correlation is introduced in the motion of electrons. A source of such correlation is certainly Pauli exclusion acting on each trap; in addition, assuming that a trap has a single level with two possible states (spin up and down), it is reasonable that Coulomb repulsion effectively forbids a second electron to occupy the other state. We discard a third effect possibly introducing additional correlation: an occupied trap could inhibit tunneling of electrons in a surrounding region by means of Coulomb repulsion. However, in the SILC regime the current not assisted by traps is negligible, and Coulomb interaction is very effectively screened by the gate and substrate planes. This means that when traps are dense enough for this last effect to be relevant, our model underestimates the correlation, and hence, the suppression of shot noise.

We consider only elastic tunneling from conduction band electrons; indeed, both inelastic scattering and tunneling from valence band electrons should be negligible for the oxide thickness considered.[9–11] Following the notation we used in the case of resonant tunneling structures,[12,13] we in-

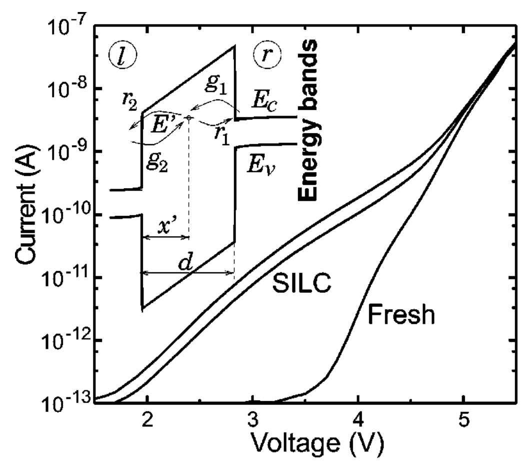

FIG. 1. Typical $I-V$ curves of fresh oxide and after two different periods of FN stress. Inset: computed band profile of the considered MOS structure with 3 V applied gate voltage.

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troduce the ''generation rates,'' i.e., the transition rates from the substrate (g_1) and from the gate (g_2) to the unoccupied trap, and the ''recombination rates,'' i.e., the transition rates from the occupied trap to the substrate (r_1) and to the gate (r_2). For gate voltages of a few volts, electrons are injected only from the substrate, so that we can discard g_2.

The transition rates can be written in a simple way if we assume that in practice only electrons with longitudinal energy E' contribute to the current, and that the trap cross section can be taken into account through a single coefficient k

$$g_1 = 2k\rho_r(E')\nu_r(E')f_r(E')T_r(E'),$$
$$r_1 = k\rho_r(E')\nu_r(E')[1-f_r(E')]T_r(E'), \quad (1)$$
$$r_2 = k\rho_l(E')\nu_l(E')[1-f_l(E')]T_l(E'),$$

where ρ_s, ν_s, and f_s $(s=l,r)$ are the density of states, the attempt frequency, and the occupation factor in the left ($s=l$) or right ($s=r$) electrode and T_l (T_r) is the tunneling probability of the one-dimensional barrier from 0 to x' (from x' to d). Recombination rates do not have the factor of 2 because only one electron with a well-defined spin can be in the trap. The average current I' through the trap can be readily obtained as $I' = qr_2(g_1+r_1+r_2)^{-1}$, where q is the electron charge, while the noise spectral density at zero frequency can be obtained with a procedure very close to that used for resonant tunneling currents[12] that will be discussed in detail elsewhere[11]

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

The shot noise suppression factor γ', or Fano factor, is defined as $\gamma' = S'/2qI'$:[4] as can be seen from (2), is between 0.5 and 1.[12]

Let us call $\sigma(E,x)$ the trap density per unit volume and unit energy. The current density per unit area J_{SILC} and its power spectral density S_{SILC} are given by

$$J_{\mathrm{SILC}} = \int\int I'\sigma dE' dx', \quad S_{\mathrm{SILC}} = \int\int S'\sigma dE' dx'. \quad (3)$$

From (2) and (3), the total Fano factor $\gamma_{\mathrm{SILC}} = S_{\mathrm{SILC}}/2qJ_{\mathrm{SILC}}$, is a weighted average of γ' and is therefore again between 0.5 and 1.

The samples considered in this study are MOS capacitors realized on (100) oriented $n+$ silicon substrates with a n epitaxy (phosphor $5\times10^{15}\,\mathrm{cm}^{-3}$). The gate oxide was grown in O_2 atmosphere. The oxide thickness is 6 nm and the active area is 0.12 mm^2. A 300-nm-thick polycristalline silicon layer was grown at 620 °C by low pressure chemical vapor deposition, 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 polycristalline silicon gate. Finally the devices were packaged in metal frames.

The experiments have been realized at room temperature using a dedicated, personal computer-based low noise measurement system. First, we measured the current–voltage ($I-V$) 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). 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.[5] Figure 1 shows the typical $I-V$ curves measured before and after stress in the Fowler–Nordheim (FN) regime.

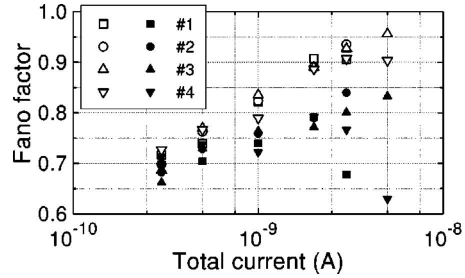

FIG. 2. Fano factor of total current γ (white symbols) and of the SILC component γ_{SILC} (black symbols) for four samples of stressed oxide as a function of the total dc current level. Sample 4 is the one considered in Fig. 1.

For a fresh oxide, at frequencies higher than few hertz, the power spectral density of the noise current S_i is equal to the full shot noise value $2qI$ and the Fano factor is 1, as expected.

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. The total current consists of a ''direct'' tunneling component (in the sense of not assisted by traps) and of a SILC component. As already said, we assume that such components are uncorrelated, i.e., that trapped electrons have a negligible effect on direct tunneling electrons. As a justication of this assumption, one can notice that in Fig. 1, for voltages larger than 5 V, when direct tunneling is predominant, the $I-V$ characteristics for stressed and fresh oxide overlap, meaning that the effect of trapped electrons on the average direct current is negligible. If I_T and I_{SILC} are the average direct tunneling and SILC currents, respectively, we can write the total noise spectrum as

$$S_i = \gamma 2qI = 2qI_T + \gamma_{\mathrm{SILC}} 2qI_{\mathrm{SILC}}, \quad (4)$$

where γ and γ_{SILC} are the suppression factor of the total current and of the SILC component, respectively, while the tunneling component exhibits full shot noise. I, S_i, and γ are known from measurements on the stressed MOS structures, I_T is assumed to be equal to the current measured before stress for same gate voltage (since the $I-V$ characteristic at large voltages does not change after stress), and γ_{SILC} is obtained from (4). In Fig. 2 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,

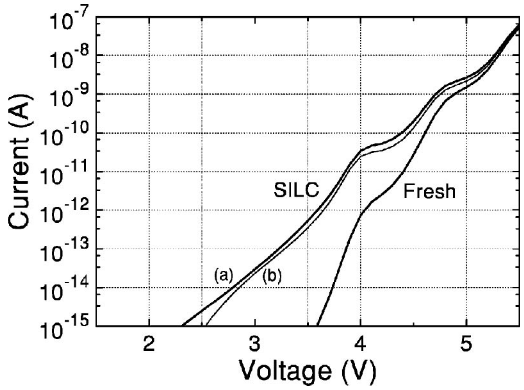

FIG. 3. Theoretical $I-V$ characteristic for a fresh oxide, and for an arbitrary concentration of traps uniformily distributed in the whole SiO_2 gap (case a–thick line) and between 1.8 and 2.0 eV below the conduction band edge of SiO_2 (case b–thin line).

results are well reproducible (within 10%) at smaller currents, where SILCs are predominant and γ_{SILC} can be extracted with a small relative error.

The model for SILCs previously described has been simulated numerically: first, we solved the nonlinear Poisson equation in order to obtain the electron density and the band profiles; then, we computed the tunneling current density and the SILC current density for an arbitrary constant value of $k\sigma$. Figure 3 shows the $I-V$ characteristic for a fresh oxide (only I_T), and for an arbitrary value of the trap density (i.e., of $k\sigma$) both for traps uniformily distributed in the gap of SiO_2 (case ''a''–thick line) and, as an example, for traps uniformly distributed between 1.8 and 2 eV below the conduction band edge (case ''b''–thin line). Lacking detailed information on the energy distribution of traps, we can reproduce only qualitatively the behavior of SILC currents.

For the same cases a and b we plot in Fig. 4 the computed γ_{SILC}. While there is a difference of 5%–10% between the two curves, the behavior is very similar and the value of γ_{SILC} is in both cases in substantial quantitative agreement with the experimental results. The oscillations in the $I-V$ curve are well known and due to resonances in the tunneling probability of a triangular barrier;[14] the same resonances cause also the oscillations of γ_{SILC}. In experiments such resonances are usually smoothed out because of interface roughness and dephasing.

In conclusion, the dc and noise behavior of the SILC regime is well reproduced by the model proposed. In particular, noise measurements demonstrate that SILCs are associated with suppressed shot noise: this suppression requires trap assisted tunneling. Indeed, the alternative mechanisms of hole trapping and conductive filament would not introduce any correlation among electrons, and therefore would be in contrast with the observed noise suppression.

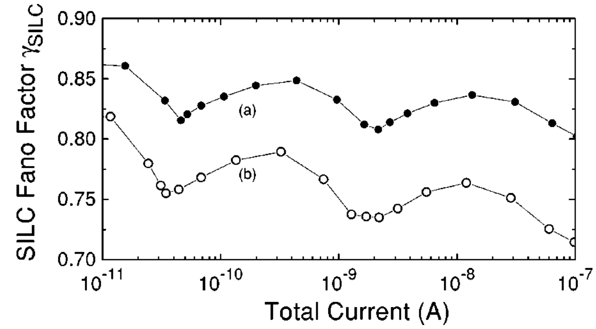

FIG. 4. Theoretical Fano factor of the SILC component as a function of the total current for cases a and b of Fig. 3.

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