Coulomb suppression of surface noise

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We have generalized the model of the surface noise taking into account the self-consistent electrostatic interaction and transverse electron transport in a conductive channel. Analyzing this model, we have found that the Coulomb correlations between trapped and conducting electrons considerably suppress the surface noise. The suppression effect is shown to be frequency dependent and especially large for noisy conducting channels. © 2001 American Institute of Physics. [DOI: 10.1063/1.1360227]

Randomness of trapping/detrapping of carriers to/from the surface states of conducting channels gives rise to electric fluctuations of current, often referred to as the surface noise. In contemporary scaled-down devices, the surface noise causes a great impact on the device performance [see e.g., recent experimental studies on amorphous and polysilicon thin-film transistors (TFTs),2 polysilicon emitter bipolar junction transistors (BJTs),3 heterostructure field-effect transistors (HFETs),4 and metal–oxide–semiconductor field effect transistor (MOSFETs)5]. The problem of the surface noise reduction is an important issue in advanced semiconductor technology.

Recently, the detailed theoretical and experimental analysis has revealed new fundamental effects in the suppression of noise in submicron and nanostructure devices. Among the examples, we may mention the shot-noise suppression due to the Pauli exclusion principle,5 Coulomb correlations,7 and the noise reduction under the size effects.8 For treating the surface noise, the currently used theoretical models ignore the Coulomb correlations and carrier transport across the channel. In this letter, we go beyond such approximations and analyze the surface noise by including the new features: (i) the transverse nonhomogeneous electrostatic transport in the conducting channel and (ii) the electrostatic (Coulomb) correlations among the trapped and channel electrons. The obtained analytical formulas demonstrate that the Coulomb correlations considerably affect the surface noise leading to a significant noise suppression.

The physical mechanism of this phenomenon can be easily understood. Indeed, the trapping rate is determined by the transverse electron flux in the channel toward the surface. The detrapping process produces the opposite electron flow. Let the number of electrons trapped on the surface be randomly increased. Then, an extra negative charge induces an electrostatic potential on the surface which decreases the incoming electron flux. This results in a decrease of the trapping rate. If the number of electrons on the surface states is randomly decreased, an extra positive surface charge and corresponding electrostatic potential stimulate the electron flux toward the surface and increase the trapping rate. For both types of the surface–charge fluctuations, the Coulomb correlations between the trapped and conducting electrons lead to decreasing in fluctuation magnitudes and suppression of the current noise. Obviously, the discussed trapping–detrapping processes, conducting channel transport, and correlations between different groups of electrons must be treated self-consistently.

To prove the above conjecture, we consider a semiconductor channel with the cross sectional area A = LxLy, near an adjacent dielectric layer. The external electric field E1 is applied along the direction z parallel to the interface (see Fig. 1). Inside the channel (y > 0), the spatial profiles of the electrostatic potential ϕ(y, t) and electron concentration n(y, t) are nonhomogeneous in transversal direction, and they are determined by the surface potential ϕs and the Fermi level ϵF (below, we use the subscript s for the values taken at the surface y = 0). The concentration of trapped electrons in the dielectric layer (y < 0) is denoted by nT(y, t), where subindex k indicates different traps levels. The basic semiclassical transport equations for nondegenerate electrons, including both steady states and fluctuations, as well as Langevin noise sources, are

\[ i_\perp(y, t) = -\mu E_1 n - D \frac{\partial n}{\partial y} + \delta j_\perp(y, t), \tag{1} \]

\[ \frac{\partial E_1}{\partial y} = \frac{\rho(y)}{\epsilon}, \tag{2} \]

\[ \frac{\partial n(y, t)}{\partial t} + \frac{\partial i_\perp}{\partial y} = 0, \tag{3} \]

FIG. 1. Schematic band-energy diagram of an electron conducting channel with traps (T) at the dielectric (D)–semiconductor (S) interface. εc is the bottom of the conduction band.

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\[ \frac{\partial n_i(y,t)}{\partial t} = S_i n_i(0,t) - K_i n_i + \delta Q_i(y,t), \]  

where \( i \) is the transverse electron flux, \( \delta J_i \) the corresponding Langevin noise source (usually called diffusion or thermal noise source), \( E_i = - (\partial \phi / \partial y) \) is the electric field perpendicular to the interface, \( \mu \) the electron mobility, \( D \) the diffusion coefficient, \( \rho(y) \) the channel charge distribution, \( \epsilon \) the dielectric constant, \( S_j \) and \( K_j \) the rate constants for trapping and detrapping processes, and \( \delta Q_k \) the trapping noise source. For the Langevin sources, the spectral correlators are standard:\(^1\)

\[ \langle \delta J_i(y) \delta J_i(y') \rangle_w = 4(D/A)n(y)\delta(y-y'), \]

\[ \langle \delta Q_k(y) \delta Q_k(y') \rangle_w = 4(K_i/A)n_k(y)\delta(y-y'), \]

where \( n_k \) is the steady-state concentration of trapped electrons. Assuming that the conducting channel is uniform in the \( xz \) plane, the electron density flux along the channel can be written as

\[ i_i(y,t) = -\mu E_i n(y,t) + \delta I_i(y,t), \]

where \( \delta I_i \) is the longitudinal Langevin flux whose correlator is similar to that for \( \delta J_i ). \(^1\) The instantaneous variables in Eqs. (1)–(5) can be split into steady-state and fluctuating quantities. The stationary problem is strongly nonlinear, however, all the quantities \( n(y), \rho(y), E_i(y), \) and \( n_k(y) \) can be found as implicit functions of \( y \) (see for example, the analysis of MOSFET’s channel).\(^10\)

Our main goal is to solve the fluctuation problem.

For the mean current along the channel we find

\[ I = q \mu E_i L_z \int_0^\infty n(y)dy, \]

where \( q \) is the electron charge. Introducing the average sheet electron density in the channel \( N = \int_0^\infty n(y)dy \) and its fluctuation \( \delta N \), one can find the noise spectral density of the channel current \( I \) in the form

\[ S_I(\omega) = 4q^2 NDL_z/L_z + (q \mu E_i L_z)^2 (\delta N \delta N^*) \]

\[ = S_{Iv} + S_{Iv}^T(\omega), \]

where \( S_{Iv} = 4k_B T R \) is the equilibrium Johnson–Nyquist contribution, \( R = L_z/(q \mu N L_z) \) is the channel resistance, and \( S_{Iv}^T(\omega) \) is the excess surface noise, which may also be written as

\[ S_{Iv}^T(\omega) = \frac{I^2 (\delta N \delta N^*)}{N^2}. \]

It is seen that the excess current noise, which is of interest here, is essentially the number fluctuation noise. To obtain its spectrum, we need to find the fluctuations \( \delta n_i(y,t) \), which are coupled self-consistently with \( \delta n_i(y,t) \) and \( \delta E_{Iv}(y,t) \). From Eq. (2) with \( \delta p = -q \delta n \) and Eq. (3), one obtains the equation for the Fourier component of the fluctuation of the transverse electric field\(^11\)

\[ \hat{L} \delta E_{\perp}(y) = -(g l \epsilon) \delta n(y), \]

where

\[ L = \frac{\partial}{\partial y} \left[ \frac{1}{W(y)} \frac{\partial}{\partial y} \right] - q \mu n(y) \frac{\partial}{\partial y} W(y), \]

\[ \delta n(y) = \delta n(y) / [D W(y)] \text{ and } W = \exp[\mu(\varphi - \varphi_0)/D]. \]

We have solved this equation and found \( \delta E_{\perp}(y) \) in an explicit form. However, since our main quantity of interest

\[ \delta E_{\perp} = \int_0^\infty \delta E_{\perp}(y)dy = (\epsilon l q) [\delta E_{\perp}(0) - \delta E_{\perp}(\infty)] \]

is determined by the boundary values, we will use an integral relation rather than an explicit form of the solution for \( \delta E_{\perp}(y) \).

The Green identity for the operator \( \hat{L} \) yields

\[ \int_0^\infty (v \hat{L} \delta E_{\perp} - \delta E_{\perp} \hat{L} v) dy = \left[ \frac{v}{W} (\delta E_{\perp}') - \frac{v'}{W} \delta E_{\perp} \right]_0^\infty, \]

where prime stands for the derivative on \( y \). It is convenient to choose \( v(y) = dE_\perp / dy = \rho \epsilon \), since it satisfies the equation \( \hat{L} v(y) = 0 \). Taking into account Eq. (9) and the boundary conditions \( \rho(\infty) = 0 \), \( \delta E_{\perp}(\infty) = 0 \) (the fluctuations far away from the surface vanish), we finally obtain

\[ \rho_j \delta n_j'' + \rho_j' \delta n_j' + \int_0^\infty \rho(y) \delta s_{\perp}(y) dy = 0. \]

To find the unknown quantities \( \delta n_j'' \) and \( \delta n_j' \), we employ the additional condition: the conservation of the total charge in the conducting channel and dielectric layer

\[ \delta N_{\perp}'' + \int_{y<0} dy \sum_k \delta n_k(\omega) = 0, \]

where the fluctuations of the trapped electrons \( \delta n_k'' \) are obtained from Eq. (4) as

\[ \delta n_k''(\omega) = \beta_k(\omega) S_k(\omega) \delta n_k' + \beta_k(\omega) \delta Q_k''(\omega), \]

with \( \beta_k(\omega) = [K_k(\omega) + i \omega]^{-1} \). Combining Eqs. (10)–(12), we obtain

\[ \delta N''_{\perp} = - \delta N''_{\perp} (1/\rho_j) \eta(\omega) \int_0^\infty \rho(y) \delta s_{\perp}(\omega) dy, \]

where \( \delta N''_{\perp} = \int_{y<0} dy \sum_k \beta_k(\omega) \delta Q_k'' \), and \( \eta(\omega) = \int_{y<0} dy \sum_k \beta_k(\omega) \delta \delta_k \). Note that \( \delta N''_{\perp} \) is related to the random trapping–detrapping processes in the dielectric, while the second integral term in the numerator is due to the random flux of electrons from the channel toward the surface. Both processes are self-consistently coupled by Coulomb correlations between the conducting and trapped electrons.

Having found \( \delta N''_{\perp} \), the fluctuation problem is solved, and we find the excess surface noise spectrum in the form

\[ S_{Iv}''(\omega) = \Gamma(\omega) S_{Iv}(\omega), \]

\[ S_{Iv}'(\omega) = \frac{I^2}{A} \times \frac{4N_z}{\omega N^2} Y_z(\omega), \]

where \( S_{Iv}'(\omega) \) is the excess surface noise with disregarded Coulomb correlations given by the conventional model of the surface noise,\(^1\) and

\[ \Gamma(\omega) = \frac{1}{[1 + \gamma Y_1(\omega)]^2 + \gamma' Y_2''(\omega)} \]

is the surface–noise–suppression factor.\(^12\) The rest of notations are: \( \gamma = (N_i/n_i) \rho_i / \rho_j, N_i \) is the sheet concentration of trapped electrons in the dielectric, \( Y_1(\omega) = \int d\tau (\tau)^{-1} g(\tau) (1 + \omega^2 \tau^2) \) with \( j = 1,2 \), and \( g(\tau) \) is the probability distribution function for the capture times \( \tau \) which run over all the values of \( 1/K_i \). It is important to highlight that the suppression factor \( \Gamma(\omega) \) is a functional of the stationary solutions taken at the surface \( E_{\perp,0} \) and \( n_z \), which in turn are determined by the surface potential \( \varphi_z \). Thus, the level of suppression \( \Gamma \) can be controlled by the gate voltage.
As an example, we consider the McWhorter model for uniformly distributed traps\textsuperscript{13,14} \( g(\tau) = 1/\tau \ln(\tau_2/\tau_1) \) at \( \tau_1 \leq \tau \leq \tau_2 \), and \( g(\tau) = 0 \) otherwise (the difference between \( \tau_1 \) and \( \tau_2 \) may constitute from five to eight decades). In Fig. 2, we show the frequency spectra of \( \Gamma(\omega) \) and the integrals \( Y_{1,2}(\omega) \). It is seen that the Coulomb suppression is significant (more than one order of magnitude) in a wide range of \( \omega \) for \( \gamma \geq 1 \). Importantly, \( Y_2(\omega) \) has a plateau in the frequency range \( 1/\tau_2 < \omega < 1/\tau_1 \). In the absence of Coulomb correlations, this leads to the well-known McWhorter result: 1/f spectrum of the surface noise within this range. One can see that the suppression factor changes only slightly over many decades for frequencies \( \omega < 1/\tau_1 \). Then, for \( \gamma \geq 1 \), \( \Gamma(\omega) \approx \Gamma(0) = 1/(1 + \gamma)^2 \), i.e., approximately constant. Thus, the 1/f law is practically preserved when the Coulomb correlations are included into analysis. For \( \omega > 1/\tau_1 \) the suppression effect vanishes \( [\Gamma(\omega) \approx 1] \), as well as the surface noise, since there are no traps with characteristic times of the order of \( 1/\omega \) and the carrier exchange between the electron channel and the traps becomes ineffective.

To make numerical estimates, consider the frequency interval within which the surface noise \( \propto 1/\omega \) with the spectrum obeying the Hooge formula: \( S_i^e(\omega) = (\Gamma/\text{NA}) \alpha_\mu \), where \( \alpha_\mu = N_e/[N(1 + \gamma)^2 \ln(\tau_2/\tau_1)] \) is the (pseudo) Hooge parameter\textsuperscript{15} \((f = \omega/2\pi)\). Now, if we take \( \gamma = 1 \), we get \( \alpha_\mu = 1.8 \times 10^{-2} \), i.e., the value usually observed in noisy conducting channels with predominant surface mechanism of the noise.\textsuperscript{14,16}

In conclusion, we have revisited the long-standing problem of the surface noise by including into the model the electrostatic interaction and transverse transport of electrons in a conducting channel. We have found that the Coulomb correlations between trapped electrons and conducting electrons contribute considerably to the phenomenon. The larger the surface noise, the greater is the contribution of the Coulomb correlations. These correlations suppress the magnitude of the surface noise in a wide frequency range, preserving the 1/f dependence.

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