CALCULATION OF THE GATE CURRENT DUE TO INJECTION OF HOT ELECTRONS INTO THE SUBGATE OXIDE OF A SUBMICROMETER MOS FIELD-EFFECT TRANSISTOR

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The gate current of a submicrometer MOS field-effect transistor is calculated using the "lucky electron" model. The main parameters of the model are estimated based on results of a kinetic Monte Carlo simulation of the electron transport.

As is well known, the gate current I_g is an extremely important electrical parameter whose variation makes it possible to estimate the time of fault-free operation of a silicon submicrometer n-channel MOS field-effect transistor (MOS-FET) in the case where injection of hot electrons into the subgate oxide is the main reason for degradation of its parameters [1]. In this connection, it is important to note that a substantial body of work (see, e.g., [1-5]) has been devoted to the problem of experimental evaluation of the current I_g in various operating regimes of the transistor and prediction of its reliability characteristics. At the same time, obtaining a reliable estimate of the gate current based on known physical models describing electron injection into the oxide is a very complex and nontrivial problem requiring *a priori* knowledge of a number of kinematic parameters characterizing the transport of hot electrons in the transistor channel under strongly nonequilibrium conditions.

The kinetic Monte Carlo method [6-11] is one of most promising methods of simulation of electronic processes occurring in submicrometer MOS-FET under these conditions. However, immediate direct calculation of the quantity I_g by this method faces the statistical problem of providing acceptable accuracy of the results obtained, since the injection of each individual electron into the subgate oxide is an extremely infrequent event [12, 13]. This can be overcome by developing combined methods that would combine the advantages of the numerical Monte Carlo method with analytical physicomathematical models describing injection of hot electrons into the subgate oxide. This approach may turn out to be especially efficient as applied to transistors with an extremely short channel, since in devices of this type small changes in linear dimensions can lead to very substantial variations in the electric-field strength and, therefore, in the kinetic parameters characterizing the electron transport under these conditions.

In what follows, we present results of calculations of the gate current I_g of a submicrometer MOS-FET using the "lucky electron" model [14, 15] with the main kinetic parameters estimated from results of a kinetic Monte Carlo simulation of the electron transport. To do this, essentially the same physicomathematical model and algorithm as in [11] were used, and therefore they are not discussed in the present work. In the simulation the following mechanisms of scattering of charge carriers were taken into account: scattering on acoustic and optical phonons, scattering on impurity ions, electron-electron scattering, impact ionization, and intervalley and interband transitions ($X \leftrightarrow L$ type transitions). Calculations of average values of the sought kinetic parameters were carried out as in [11].

The gate current I_g, according to the "lucky-electron" model, is calculated by the formula [14, 15]:

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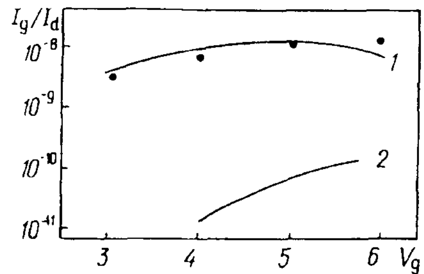


Fig. 1. Dependence of the gate-current-to-drain-current ratio I_g/I_d on the gate voltage V_g, V.

$$I_g = I_d \int_0^{L_{ch}} \frac{P_1 P_2}{\lambda_r}\, dx . \tag{1}$$

Based on results of the same works, expression (1) can be rewritten as follows:

$$I_g = 0.025 I_d \int_0^{L_{ch}} \frac{\varepsilon_x \lambda_h}{\Phi_b \lambda_r} \exp\left(-\frac{\Phi_b}{\varepsilon_x \lambda_h}\right) P_2 dx , \tag{2}$$

where the parameter Φ_b equals

$$\Phi_b = 3.2 - \beta \sqrt{\varepsilon_{ox}} - \gamma \sqrt[3]{\varepsilon_{ox}^2} .$$

The values of the coefficients β and γ, according to [15], are as follows: $\beta = 2.59 \cdot 10^{-5}$ $V^{1/2} \cdot m^{1/2}$ and $\gamma = 1.86 \cdot 10^{-6}$ $V^{1/3} \cdot m^{2/3}$

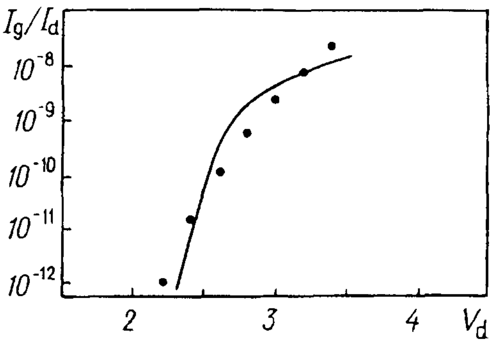
The probability P_2 can be written as follows:

$$P_2 = \left\{ \frac{5.66 \cdot 10^{-8}\, \varepsilon_{ox}}{(1 + 6.9 \cdot 10^{-8}\, \varepsilon_{ox})\, [1 + 2 \cdot 10^{-5}\, L_{ch}^{-1} \exp(-0.67\, \varepsilon_{ox}\, d_{ox})]} + 2.5 \cdot 10^{-2} \right\} \exp\left(-\frac{3000}{\sqrt{\varepsilon_{ox}}}\right), \quad \varepsilon_{ox} \ge 0 ;$$

$$P_2 = 2.5 \cdot 10^{-2} \exp\left(-\frac{d_{ox}}{\lambda_{ox}}\right), \quad \varepsilon_{ox} < 0 . \tag{3}$$

Thus, with the drain current I_d known, one can estimate the gate carrent by calculating the integral in formulas (1) and (2). In doing this, the parameters λ_h and λ_r are considered as constants within the framework of the "lucky electron" model. So, according to [1], $\lambda_h = 7.8$ nm, and in [16] the value of $\lambda_r = 61.6$ nm was obtained. At the same time, the following is evident: since the electron mean free path in the transistor channel is determined by various scattering mechanisms that depend on the electric-field strength, concentration of the ionized impurity, quality of the oxide-semiconductor interface, and other structural and technological parameters, λ_h and λ_r in each particular case will have different values. For example, e.g., it has been shown in [17] that the value of λ_h decreases with increasing longitudinal field ε_x. Neglecting this circumstance leads to considerable error in evaluation of the current I_g by formulas (1) and (2).

Another, no less important reason leading to inaccuracy of evaluation of the current by the analytical model of "lucky electrons" is the use of simple approximations for the parameters ε_x, ε_{ox}, and Φ_b that do not account for the actual field distributions in the device. These assumptions can be especially crude in the case of MOS-FET with very short channels, since the electric fields vary substantially with distance in these transistors, and the actual values of the field strengths can be found only by solving Poisson and Boltzmann equations numerically. Taking these circumstances into account, in the present work we determined the parameters λ_h, λ_r, ε_x, ε_{ox}, and Φ_b from results of a self-consistent simulation of the electron transport in the channel of an MOS transistor, and integration in Eqs. (1) and (2) was carried out numerically.



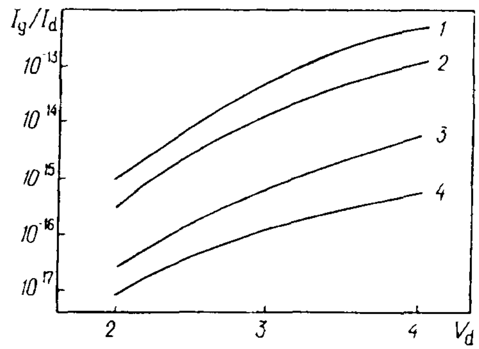


Fig. 2. Dependence of the gate-current-to-drain-current ratio I_g/I_d on the drain voltage V_d, V.

Fig. 3. Dependence of the gate-current-to-drain-current ratio I_g/I_d on the drain voltage V_d at different temperatures T and channel lengths L_{ch}.

Figure 1 presents dependences of the ratio of currents I_g/I_d on the gate voltage V_g at a drain voltage V_d = 3 V for two values of the thickness of the subgate oxide d_{ox} = 7.5 nm (curve 1) and d_{ox} = 20 nm (curve 2), calculated at a temperature T = 300 K for an MOS-FET with a channel length L_{ch} = 0.1 μm. The points show experimental data [5] obtained under the same conditions as curve 1. The results of the theoretical calculation are in a good agreement with the experiment. It should be noted that an increase in the oxide thickness from 7.5 to 20 nm leads to a considerable decrease in the gate current. This behavior of the curves is connected with the fact that the probability that a hot carrier traverses the subgate oxide decreases with increase in d_{ox}. This statement agrees completely with Eq. (3) and experimental data available from the literature.

Figure 2 presents the ratio I_g/I_d as a function of the drain voltage V_d at a fixed gate–drain potential difference $V_g - V_d$ = 0.05 V and a thickness of the subgate oxide d_{ox} = 7.5 nm (curve 1). The remaining parameters needed for the calculation are the same as in Fig. 1. The points correspond to experimental results [5], which substantiate the validity of our theoretical calculations. In particular, it follows from Fig. 2 that a change in the drain voltage by less than twofold leads to an increase in the ratio I_g/I_d by several orders of magnitude. This becomes understandable if one takes into account the fact that even a small increase in the drain voltage in transistors with a short channel leads to a sharp increase in the energy of the charge carriers in the immediate vicinity of the drain and, therefore, to a substantial increase in the number of electrons with an energy exceeding Φ_b.

Figure 3 presents results of calculations of the dependence of the ratio I_g/I_d on the voltage V_d at an oxide thickness d_{ox} = 20 nm and a gate voltage V_g = 1 V for temperatures T = 77 K (curves 1 and 2) and T = 300 K (curves 3 and 4) and channel lengths L_{ch} = 0.2 μm (curves 1 and 3) and L_{ch} = 0.5 μm (curves 2 and 4). The following conclusions can be drawn from an analysis of the dependences. First, the gate current decreases with increasing temperature. This is explained by the fact that at a higher temperature the intensity of scattering of electrons on optical phonons with emission of the latter will increase and, therefore, the mean free path of hot electrons λ_h will decrease accordingly. As follows from Eq. (2), the gate current I_g will also decrease in this case. Secondly, a considerable decrease in the current I_g with increasing channel length L_{ch} is observed, which is connected with a decrease in the longitudinal field in the channel.

Thus, the results obtained in the present work indicate that a combined approach based on the use of a numerical kinetic Monte Carlo simulation and the analytical model of "lucky electrons," which has been proposed in the present work, is a rather efficient means of solving the problem of evaluating the gate current due to injection of hot electrons into the subgate oxide of a silicon submicrometer MOS-FET.

NOTATION

I_d, drain current; L_{ch}, transistor channel length; P_1, probability that an electron, while moving in the channel, acquires an energy sufficient for overcoming the potential barrier at the oxide/semiconductor interface;

P_2, probability that a "lucky electron" reaches the gate from a point of the channel where it had an energy sufficient for overcoming the potential barrier; λ_r, mean free path of electrons between two successive collisions not accompanied by substantial loss of energy; ε_x, strength of the field directed along the channel (i.e., the longitudinal field) at a cross section located a distance x from the source; λ_h, mean free path of hot electrons having an energy sufficient for injection into the oxide; Φ_b, width of the potential barrier at the oxide/semiconductor interface: $\varepsilon_{ox} = (\varphi_g - \varphi_s)/d_{ox}$; φ_g, gate potential; φ_s, surface potential; d_{ox}, thickness of the subgate oxide; λ_{ox}, mean free path of electrons in the oxide, equal to 3.2 nm [15].

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