Impact Ionization Process in Deep Submicron MOSFET

Dmitry Speransky, Andrei Borzdov, and Vladimir Borzdov

***Abstract*—Within the framework of Keldysh impact ionization model the calculation of effective threshold energy for silicon MOSFET with 100 nm channel length by means of ensemble Monte-Carlo simulation is performed. The possibility of impact ionization rate treatment with one-parameter Keldysh model in pre-breakdown and breakdown transistor operation mode using calculated effective threshold energy value is proposed.**

***Index Terms*—MOSFET, Monte-Carlo, impact ionization, threshold energy**

I. Introduction

It is known that in numerical simulation of integrated circuit elements along with the reduction of the device dimensions, particularly MOSFETs, taking into account an impact ionization process becomes essential. The latter is caused by the fact that the rate of impact ionization in such elements can be comparable or even greater than the rates of other considered scattering processes resulting from the presence of high electric field.

It is also known that one of the most powerful submicron MOSFET simulation methods with account of all dominant mechanisms of charge carrier scattering including impact ionization is an ensemble Monte-Carlo procedure (see, for example, [1–3] and references therein).

The main purpose of this study is the estimation of impact ionization effective threshold energy in deep submicron silicon n-channel MOSFET with 100 nm channel length in the framework of Keldysh impact ionization model.

II. Threshold Energy Of Impact Ionization

Impact ionization is a threshold process [4]. In the simple case, the value of threshold energy E_{th} is defined using energy and momentum conservation rules. It can be shown that in case of two simple parabolic bands impact ionization threshold energy $E_{th} \approx \frac{3}{2} E_g$, where E_g is the band gap of silicon. However, in case of accurate impact ionization process simulation in bulk silicon or in silicon device structures one must take into account the fact that silicon has a complex energy band structure. Furthermore considering high energy carriers, it's important to take into account the band nonparabolicity and anisotropy. Subject to this in [5] the method of threshold energy estimation in several semiconductors with different band structures has been proposed. It has been taken into account that different values of the threshold energy are possible and it has been concluded that effective (or some averaged) threshold energy for charge carriers may depend on electric field.

If carrier energy is equal to E_{th} then the impact ionization cross section becomes zero. After collision there are three particles (ionizing electron and generated electron and hole pair) in three different final states. Thus by analyzing a density of states it might be expected that above E_{th} the cross section is a strongly monotonically increasing function of electron energy [4].

If we denote momentums of the final states of electrons and a hole by p_1 , p_2 , p_3 respectively, the probability of impact ionization per unit time which is proportional to the cross section may be expressed according to the first Born approximation as follows [6]:

$$W_i(E_0) = \frac{2\pi}{\hbar} V^3 \int \left| M(p_0, p_1, p_2) \right|^2 \times \\ \times \delta\left[E_e(p_0) - E_e(p_1) - E_e(p_2) + E_h(p_3) \right] \times \\ \times \delta\left[\frac{p_0 - p_1 - p_2 + p_3}{\hbar} \right] \frac{d^3 p_1 d^3 p_2 d^3 p_3}{(2\pi\hbar)^9}^2, \quad (1)$$

where p_0 and E_0 are the initial momentum and energy of the ionizing electron, $E_e(p_1), E_e(p_2), E_h(p_3)$ are energies of the final states of electrons and a hole respectively, M is the corresponding matrix element of the transition, V is the volume of the unit cell if the reduced Brillouin-zone scheme is considered, δ is the delta function.

In Monte-Carlo simulations of semiconductor electrical properties the so-called Keldysh formula is widely used for calculation of impact ionization scattering rate $W_{II}(E)$ with given threshold energy E_{th} [6]:

$$W_{II}(E) = A W_{ph}(E_{th}) \left(\frac{E - E_{th}}{E_{th}} \right)^2, \quad (2)$$

where A is a fitting parameter, $W_{ph}(E_{th})$ is the total electron-phonon scattering rate at the energy equal to E_{th}. Thus the model has two fitting parameters A and E_{th} with

This work was supported by the Ministry of Education of Belarus, project "Electronics 1.1.03".

D. Speransky, A. Borzdov, and V. Borzdov are with the Radiophysics and Computer Technologies Department, Belarussian State University, Minsk, Belarus (e-mail: dmitry.speransky@gmail.com)

Copyright © 2012 by Department of Microelectronics & Computer Science, Technical University of Lodz

E_{th}^{soft} = 1.2 eV for "soft" and E_{th}^{hard} = 1.8 eV for "hard" thresholds [2]. A difference between these two models may be described as follows. In the hard threshold model it is assumed that during the impact ionization event the rules of energy and momentum conservation must be preserved. In the soft threshold model a participation of phonons in the impact ionization process is expected. Due to this the restriction associated with the rule of momentum conservation may be neglected [7]. There is no common point of view on what values of E_{th} and A should be chosen exactly. The value of A may vary, and we have used A = 0.38 and A = 100 for soft and hard thresholds respectively [7].

In general, the effective threshold energy depends on the maximum of the product of an exponentially decreasing distribution function and an increasing ionization cross section [8]. If the effective cross section increases rapidly along with the energy, then it may be concluded that the value of effective ionization energy will be close to threshold energy (within the limits of 0.1 eV) [4]. However there may be some exceptions from this rule, such as for silicon. Using a realistic band structure described in [8] the ionization probability per unit time for electrons in silicon was calculated. According to these results the ionization cross section decreases down to zero at a threshold of 1.1 eV. At the same time it is worthwhile to note that the increase of the cross section is very smooth. Thus it may be concluded that the effective ionization threshold energy might be much higher than the 1.1 eV threshold [4, 8].

III. MOSFET Feature Simulation

Monte-Carlo simulation of the MOSFET using MOSFET software package developed by the authors, has been performed to determine the influence of the drain voltage V_D on effective threshold energy value E_{theff} at two gate voltages V_G = 1 and 2 V. A structure of the device under consideration and some aspects of the simulation algorithm are described, in particular, in [3, 7, 9 –11]. Electron transport simulation in silicon conduction band includes X and L valleys with account of the band nonparabolicity. Electron scattering processes are intravalley acoustic and intervalley phonon scattering, optical phonon scattering in L-valley, ionized impurity scattering, plasmon scattering and impact ionization process. Holes are treated in quasi-equilibrium approximation for simplicity. In other words it is supposed that the hole distribution function is similar to Maxwellian with temperature T and concentration N_i which satisfies the current continuity equation [7]. Source and drain are modeled as ideal ohmic contacts and metal gate is assumed to be aluminum. The simulation has been done for the temperature T = 300 K. The MOSFET structure and dimensions are specified in Fig. 1. Other parameters are as follows: the gate oxide thickness is 10 nm, acceptor doping levels of the channel and substrate are equal to $5\cdot10^{23}$ m^{-3} and 10^{24} m^{-3}, donor doping level of the source and drain regions is equal to $8\cdot10^{24}$ m^{-3}.

One of the relevant characteristics describing device behavior in the impact ionization regime are the impact ionization scattering rate $W_{II}(E)$ and the electron distribution functions $f(E)$ near the drain end of the transistor channel, where E is measured from the bottom of the conduction band. Close to the drain the impact ionization rate is the highest. Both parameter characteristics vs electron energy E and for different bias conditions are shown in Fig. 2 and Fig. 3. The characteristics have been calculated at temperature T = 300 K for L_{ch} = 100 nm and L_{ch} = 50 nm respectively.

As appears in Fig.2 and Fig.3, the nature of $f(E)$ dependence is not changed with decreasing the channel length up to 50 nm. It is confirmed by the dependence of the longitudinal electric field versus x-coordinate (along the transistor channel) which is shown in Fig. 4. Furthermore, a monotonous increase of $W_{II}(E)$ with the increase of the primary carrier energy from 1.2 to 3 eV for soft threshold indicates that effective impact ionization threshold energy may be significantly higher than minimum threshold which is approximately equal to the energy gap of 1.1 eV in silicon at T = 300 K.

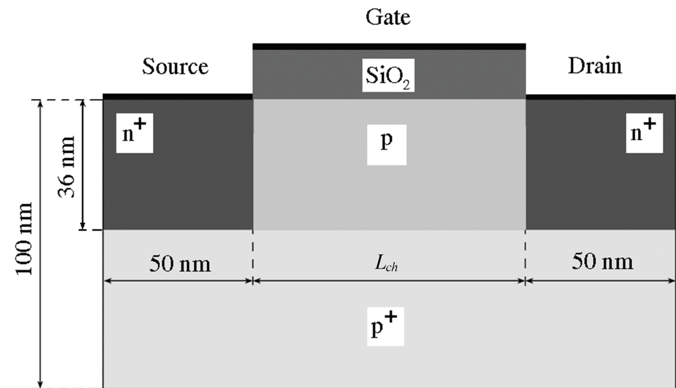

Fig. 1. Cross-section of simulated MOSFET.

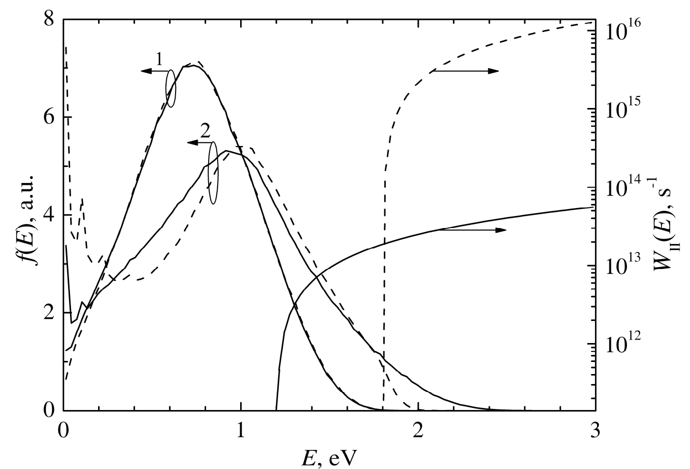

Fig. 2. Electron distribution functions f (E) and impact ionization scattering rates $W_{II}(E)$ versus electron energy E in the transistor with 100 nm channel length for soft threshold (solid curves) and hard threshold (dashed curves) models at V_G = 2 V. Curves 1 – V_D = 2 V, and curves 2 – V_D = 3 V.

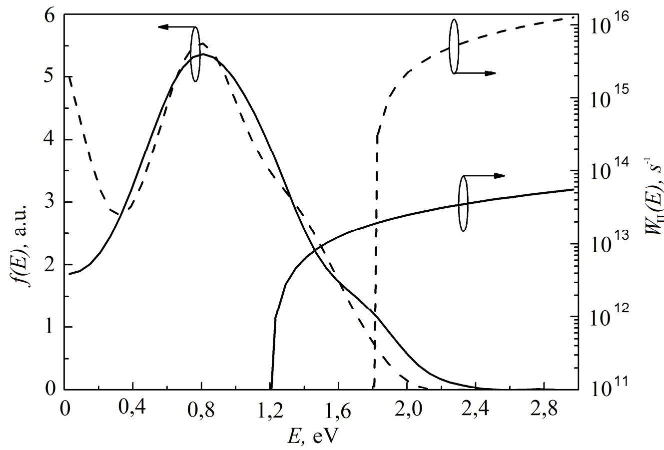

Fig. 3. Electron distribution functions $f(E)$ and impact ionization scattering rates $W_{II}(E)$ versus electron energy E in the transistor with 50nm channel length for soft threshold (solid curves) and hard threshold (dashed curves) models at $V_G = 1$ V and $V_D = 3$ V.

According to the approach proposed in [8] the effective threshold energy value in MOSFET channel can be estimated utilizing the criterion of maximum product of impact ionization scattering rate $W_{II}(E)$ and electron distribution function $f(E)$ for energy values larger than minimum threshold. It should be noticed that in this case the value of impact ionization effective threshold energy E_{theff} can be considered as energy value for which the maximum number of scattering events in a unit of time for simulated ensemble of primary electrons occurs.

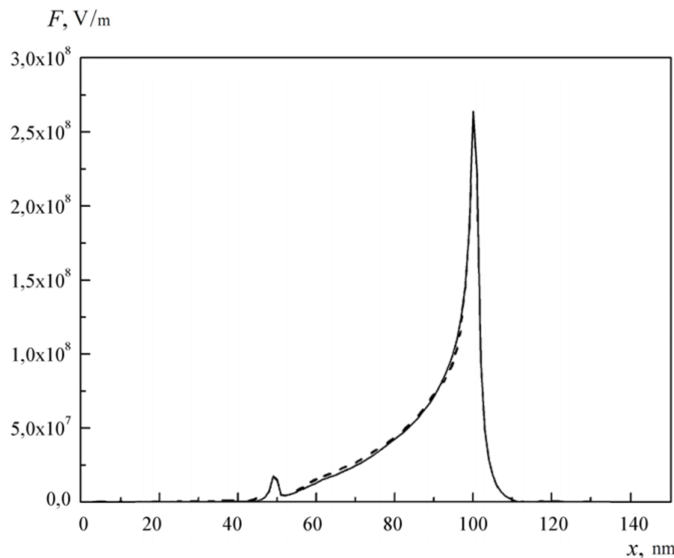

Fig. 4. The dependence of electric field F versus the coordinate x along the MOSFET channel for soft (solid curves) and hard (dashed curves) thresholds, $L_{ch} = 50$ nm.

In Fig. 5 the dependence of E_{theff} versus the drain voltage V_D for the gate voltages $V_G = 1$ and 2 V is shown. As can be seen from the figure it is possible to mark out three regions in the dependence of E_{th} versus V_D:

I) Interval: 0.5 V < $V_D \leq 1$ V: it is the range of constant values of $E_{th}^{soft} = E_{theff}^{soft} = 1.2$ eV and $E_{th}^{hard} = E_{theff}^{hard} = 1.8$ eV; E_{th}^{soft} and E_{th}^{hard} do not depend on V_D.

II) Interval: 1 V < $V_D \leq 3$ V: it is the range of almost linear growth of effective threshold energy both for soft and hard thresholds.

III) Interval: 3 V ≤ V_D: it is the range of almost constant $E_{theff}^{hard} = 1.88$ eV, which is close to $E_{theff}^{soft} = 1.7$ eV and differs from the last not more than by approximately 0.2 eV.

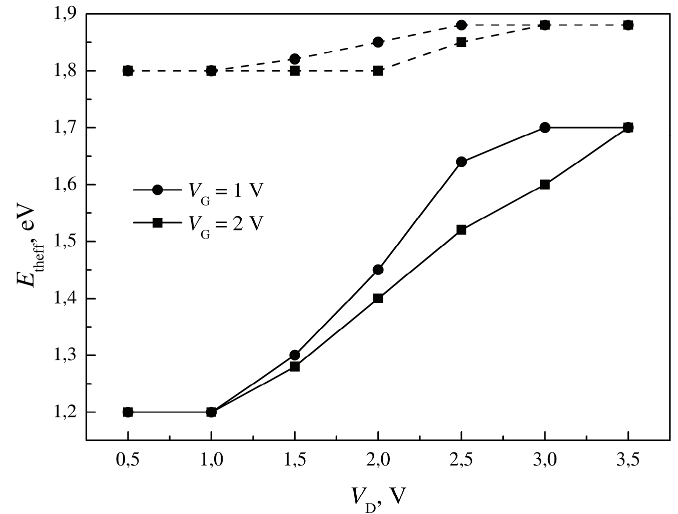

Fig. 5. Effective threshold energy E_{theff} versus drain voltage V_D dependence for soft (solid curves) and hard (dashed curves) thresholds.

Current-voltage characteristics of the simulated MOSFET are presented in Fig. 6. Comparison of Fig. 5 and Fig. 6 allows one to make a conclusion that region I corresponds to the nearly linear transistor operation mode with saturation region passage. Region III corresponds to pre-breakdown mode when strong avalanche multiplication occurs. Region II corresponds to the transition range from a saturation to pre-breakdown mode.

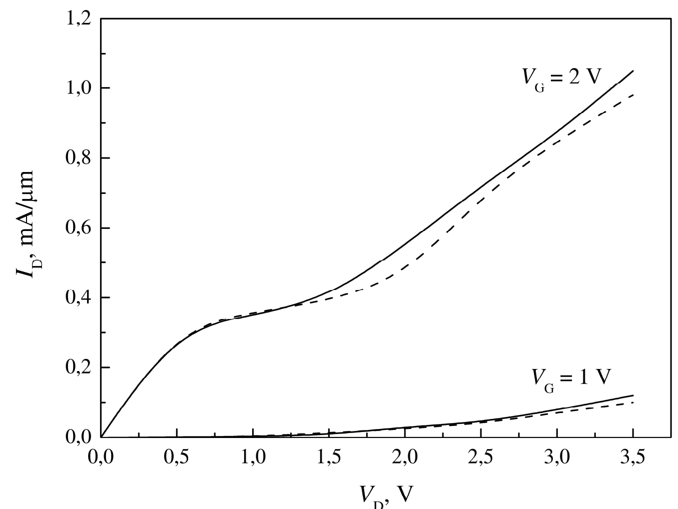

Fig. 6. Simulated current-voltage characteristics of the MOSFET with the use of soft threshold (solid curves) and hard threshold (dashed curves) models.

As may be seen from the Fig. 2 and Fig. 6 for a rather high drain bias when a strong electric field exists in the MOSFET channel the effective threshold energy of impact ionization process does not depend sufficiently on the choice of Keldysh model type. The latter may be explained by the fact that high electric field is localized near the drain end of the channel (in approximately 20 nm region) and electrons gain enough energy during the free flight time to make an impact ionization act according to both soft and hard threshold models. Obtained results remain to some extent in agreement with those of [12] where effective threshold energy in Si was calculated taking into account its dependence on the wave vector of primary electrons. It was shown there that in a uniform electric field of strength $\leq 5\cdot10^7$ V/m the effective threshold energy was approximately 1.7 eV. Also according to [13] for $A = 100$ and electric field strength of $4\cdot10^7$ V/m the deviation of the effective threshold energy from the hard threshold appears to be approximately 0.12 eV which is close to our value of approximately 0.08 eV.

IV. Conclusion

In conclusion it should be noticed that in current work the impact ionization effective threshold energy in deep submicron MOSFET with channel length of 100 nm was defined in the framework of Keldysh model. Calculations were done by means of ensemble Monte-Carlo simulation for drain biases in the interval from 0.5 to 3.5 V and gate biases $V_G = 1$ and 2 V. Corresponding transistor current-voltage characteristics were calculated. Analysis and comparison of calculated $E_{\text{theff}}(V_D)$ and $I_D(V_D)$ dependences for soft and hard threshold models let us see that in pre-breakdown operation mode the difference between $E_{\text{theff}}^{\text{hard}}$ and $E_{\text{theff}}^{\text{soft}}$ is approximately 0.2 eV. The latter allows us to conclude that in numerical simulations of the MOSFET characteristics in pre-breakdown and breakdown regimes it is possible to use Keldysh impact ionization model with only one fitting parameter A. Effective threshold energy in that case is *a priori* known and may be taken as average value of effective energies for soft and hard thresholds, which is approximately equal to 1.8 eV (see Fig. 5). Also the validity of application of one-parameter model for the simulation of very short channel MOSFETs in various regimes of operation, apparently, must be investigated.

References

[1] M. V. Fischetti, S. E. Laux, Monte Carlo analysis of electron transport in small semiconductor devices including band structure and space-charge effects, Phys. Rev. B, 1988, Vol. 38, pp. 9721–9745.

[2] C. Jacoboni, P. Lugly, The Monte Carlo Method for Semiconductor Device Simulation, Wien–New York: Springer-Verlag, 1989

[3] V.M. Borzdov, O.G. Zhevnyak, V.O. Galenchik, F.F. Komarov, Monte-Carlo simulation of integral electronics device structures, Minsk: Belarus State University Publishing, 2007 (in Russian)

[4] F. Capasso, Physics of avalanche photodiodes, in Semiconductors and semimetals (Lightwave communication technology, vol 22, Part D. Photodetectors), ed. R. K. Willardson and A. C. Beer, Orlando: Academic Press, 1985, pp. 2–168.

[5] C.L. Anderson, C.R. Crowell, Threshold energies for electron-hole pair production by impact ionization in semiconductors, Phys. Rev. B, 1972, Vol. 5, no. 6, pp. 2267–2272.

[6] L.V. Keldysh, Concerning the Theory of Impact Ionization in Semiconductors, Soviet Physics JETP, Vol. 21, no. 6, 1965, pp. 1135–1144.

[7] N.A. Bannov, O.I. Kaz'min, Simulation of highly nonequilibrium electronic phenomena in submicron silicon MOSFETs, Mikroelektronika, Vol. 18, no. 2, 1989, pp. 112–125 (in Russian).

[8] E. O. Kane, Electron scattering by pair production in silicon, Phys. Rev., 1967, Vol. 159, no. 3, pp. 624–631.

[9] D.S. Speransky, A.V. Borzdov, V.M. Borzdov. Impact ionization effective threshold energy estimation in MOSFET with 50-nm channel length / Proc. 21st International Crimean Conference" Microwave and Telecommunication Technology". CriMiCo 2011, Sevastopol, Ukraine, 2011, pp. 810-811.

[10] R. Rengel, J. Mateos, D. Pardo, T. Gonzalez, and M.J. Martin, Monte Carlo analysis of dynamic and noise performance of submicron MOSFETs at RF and microwave frequencies, Semicond. Sci. Technol., 2001, Vol. 16, pp. 939–946.

[11] D. Vasileska, The role of quantization effects on the operation of 50 nm MOSFET and 250 nm FIBMOS devices, Phys. Status Solidi b, 2002, Vol. 223, no. 1, pp. 127–133.

[12] N. Sano, M. Tomizawa, A. Yoshii, Monte Carlo analysis of ionization threshold in Si, Appl. Phys. Lett., 1990, Vol. 56, no. 7, pp. 653–655.

[13] R. Chwang, C.R. Crowell, Effective threshold energy for pair production in nonpolar semiconductors, Solid State Commun., 1976, Vol. 20, no. 3, pp.169–172.

Dmitry Speransky is pursuing Ph.D. degree in electronics. He is currently a researcher with the Laboratory of materials and device structures of micro- and nanoelectronics, department of Radiophysics and Computer Technologies, Belarusian State University. His research topic is computer simulation of semiconductor electron devices, particularly deep submicron MOSFETS.

Andrei Borzdov received Ph.D degree in electronics from Belarusian State University, Minsk, Belarus, in 2010.
Currently he is a researcher with the Laboratory of materials and device structures of micro- and nanoelectronics, department of Radiophysics and Computer Technologies, Belarusian State University. His research interest is computer simulation of semiconductor electron devices, particularly short channel MOSFETS and SOI MOSFETS.

Vladimir Borzdov received Ph.D. degree in physics and degree of a doctor of sciences in the physics of condensed matter, solid-state electronics, micro- and nanoelectronics from Belarusian State University, Minsk, Belarus, in 1986 and 1999, respectively. Currently he is a professor and a leading researcher with the Laboratory of materials and device structures of micro- and nanoelectronics, department of Radiophysics and Computer Technologies, Belarusian State University. His research interests lay in the sphere of statistical physics, physics of semiconductors and theory of Monte Carlo method in application to semiconductor device simulation.