MONTE CARLO SIMULATION OF PULSED LASER IRRADIATION EFFECT ON ELECTRICAL CHARACTERISTICS OF SUBMICRON SOI MOSFET

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Self-consistent ensemble Monte Carlo simulation of charge carrier transport in submicron SOI MOSFET is performed. A short-channel SOI MOSFET with 100 nm channel length is considered. The transistor drain current response under the effect of picosecond pulsed laser irradiation is calculated. The simulation is done for the irradiation power density of $5 \cdot 10^{10}$ W/m^2 for 532 nm and 650 nm wavelengths. Time dynamics of the drain current density under the irradiation effect has been investigated for several values of the drain bias.

Keywords: laser irradiation; Monte Carlo simulation; SOI MOSFET.

Introduction

One of the most important issues in electronics design and manufacturing is durability of ICs under the effect of external irradiation. As the dimensions of the IC elements decrease their sensitivity to so called single event upsets (SEU) increases. SEUs may be produced by the incidence of particles with high energies, for instance heavy ions. The main effect of the transition of such particles through the IC element consists in the generation of additional mobile charge (electron-hole pairs) which may cause failure in the operation of logical ICs [1, 2].

Experimental investigation of SEU effects produced by high energy particles meets some difficulties in the realization of the experimental equipment and the interpretation of experimental results. In that case imitation of SEU effects by the pulsed laser irradiation is a very attractive technique [3, 4]. The influence of the laser pulse results in generation of electron-hole pairs in the irradiated region due to photoelectric effect and thus emulates the passage of a high energy particle through the device. Among the advantages of the imitation by laser irradiation are better temporal and spatial control of the incident laser beam, and availability and lower costs of the equipment in comparison with ion beam accelerators.

Numerical simulation of pulsed laser irradiation effects on IC elements (such as MOSFETs) must also be very helpful additional tool in experimental investigations of SEUs. In some cases, the computer simulation may fully replace real experiments making the investigation faster and reducing design costs. Computer simulation can also be used to calibrate laser experimental equipment and to select the laser beam parameters in order to better emulate the passage of a high-energy particle through the tested device.

Silicon submicron SOI MOSFETs are the main elements of many modern ICs. Thus, the investigation of radiation hardness of SOI MOSFETs is a very important problem. The aim of our work is Monte Carlo simulation of the drain current response of typical short-channel SOI MOSFET on the effect of pulsed laser irradiation and to study the timescale of the current decay after the effect for several operation regimes of the transistor.

Monte Carlo simulation model

Numerical simulation of SOI MOSFET electrical characteristics by means of ensemble Monte Carlo procedure has been widely used by now [5, 6]. The advantage of ensemble Monte Carlo method is the possibility to track the charge carrier trajectories in the real and momentum spaces under various conditions and calculate corresponding distribution functions and kinetic parameters. The method allows inclusion of different charge carrier scattering mechanisms, generation and recombination processes. The Monte Carlo charge transport simulation procedure is often complemented with the self-consistent calculations of charge densities and electric fields inside the device which makes the method especially powerful tool for the simulation of semiconductor devices.
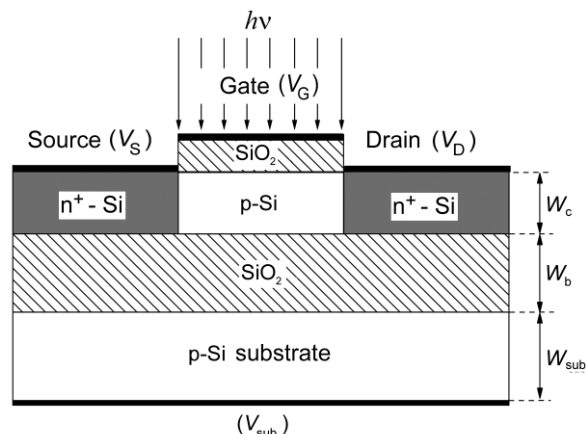

Fig. 1. The cross-section of simulated SOI MOSFET

The studied submicron SOI MOSFET has analogous structure to that regarded in our previous works [7, 8]. The cross-section of the device is presented in the figure 1. Main dimensions of the transistor are as follows: the channel length is 100 nm, the gate oxide width is 5 nm, the channel width $W_c = 50$ nm, the width of the buried oxide $W_b = 145$ nm, the substrate width $W_{sub} = 200$ nm. The channel doping level is supposed to be 10^{21} m^{-3}. The lattice temperature for the simulation is 300 K.

The Monte Carlo charge transport model is shortly described as follows. Electron and hole charge

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transport is taken into account. The hole charge accounts only for holes generated by laser radiation. In present work we neglect size quantization effects and consider electron and hole gases as purely three-dimensional. Such approximation must be reasonable for considered transistor channel width. Also, for SOI MOSFETs with thinner channels, size quantization effects must be accounted for while simulating charge carrier transport.

Electron scattering by ionized impurities, acoustic and optical phonons is included. The same mechanisms are regarded for holes. Impact ionization processes are included into our simulation procedure, however they don't make any sufficient contribution to the drain current for considered regimes of operation. When electron and hole gases are three-dimensional the charge carrier scattering by Si-SiO$_2$ interfaces is usually regarded as the combination of diffusive and specular reflections of particles from an interface. The amount of diffusive scattering must depend on the quality of the interface and is not *a priory* known. Variation of the amount of diffusive scattering influences, for example, drift velocity and particle distribution functions in the transistor channel. As a result it also makes an influence on current-voltage characteristics of the device and may be used as additional fitting parameter in Monte Carlo transport simulations. Since it is not the aim of current work to examine the role of interface scattering on the transport properties, electron and hole scattering by Si-SiO$_2$ interfaces is regarded as purely specular.

Electrostatic potential and electric field strength within the device as well as other physical parameters of interest are calculated via incorporating the solution of two-dimensional Poisson equation into the Monte Carlo simulation procedure. The Poisson equation is solved after every time step Δt of charge carrier transport simulation in order to update the electrostatic potential. Monte Carlo procedure is two-dimensional in real space and three-dimensional in momentum space. The simulation is performed using particle technique and the Poisson equation is solved using appropriate boundary conditions. The time step Δt is chosen to be 1 fs.

Electrodes of the drain, the source, and the substrate are treated as ideal ohmic contacts, while the metallic gate is assumed to be aluminum. Ideal ohmic contact model implies that a contact is in thermal equilibrium though the current is flowing through it. The latter means that the contact injects particles to provide charge neutrality in a small region of semiconductor near the contact edge. We suppose that injected particles have Maxwellian distribution and also we use the injection model which takes into account that particles are not injected simultaneously. Particles reaching the contact from inside the simulation domain leave the device freely.

In present study we suppose a normal incidence of the laser beam to the gate plane. We suppose that the laser radiation covers only the gate region and thus neglect its effect on the source and drain regions. The laser pulse studied here has 1 ps duration at 532 and 650 nm wavelength. As an approximation the laser pulse has a uniform in time power density of $5 \cdot 10^{10}$ W/m^2. Also, we admit the approximation that the gate electrode is transparent for radiation. This approx-

imation may be reasonable for a very thin metallization, or for the use of other gate structures. In practice some part of radiation will be reflected by the gate, so that the results of calculations should be shifted to higher power densities then currently used.

The SiO$_2$ is purely transparent for the regarded wavelengths. The photon absorption and electron-hole pair generation in silicon is treated according to the fundamental band-to-band absorption process. Each photon is assumed to produce only one electron-hole pair. For every photon entering the transistor channel its travel length is simulated according to Beer's law taking into account possible multiple reflections from Si-SiO$_2$ boundaries. The absorption coefficient for silicon and optical parameters of materials at 300 K are taken from [9, 10].

Simulation results and discussion

In the figures 2 and 3 the calculated transient response of the transistor drain current density on the pulsed laser irradiation is presented.

The source, gate and substrate electrode biases are zero for all calculations. Laser pulse starts at $t = 0$. For clearness the time is presented in logarithmic scale.
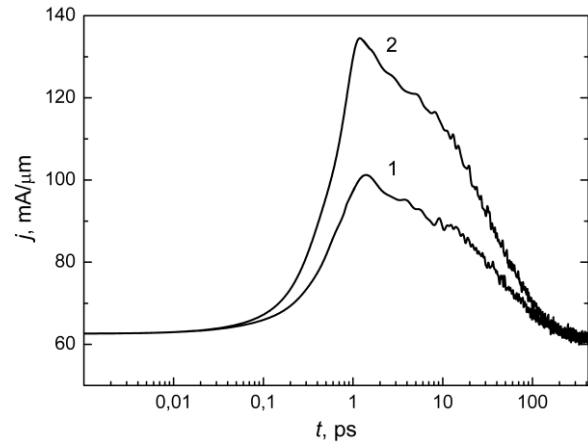

Fig. 2. Drain current response of the SOI MOSFET on the picosecond pulsed laser irradiation. Curve 1 corresponds to the wavelength of 650 nm, curve 2 corresponds to the wavelength of 532 nm. The drain bias $V_D = 1$ V
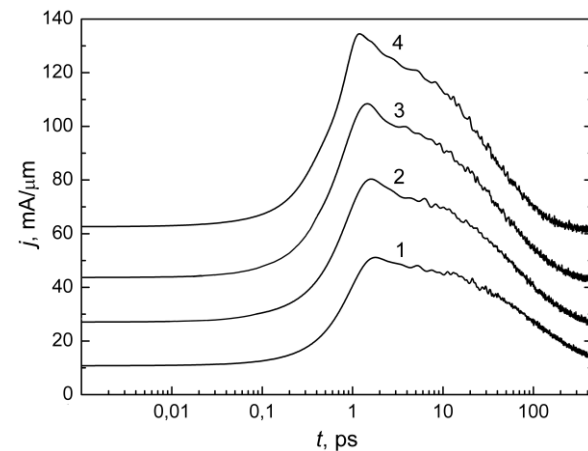

Fig. 3. Drain current response of the SOI MOSFET on the picosecond pulsed laser irradiation with 532 nm wavelength. Curve 1 corresponds to the drain bias $V_D = 0.25$ V, $2 - V_D = 0.5$ V, $3 - V_D = 0.75$ V, $4 - V_D = 1$ V

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Calculated drain current density versus time dependence represents fast rise for the first 1.5 ps and a slow decay during approximately 400 ps. For the applied gate and substrate biases and without illumination the transistor is not in the off-state since the drain currents are not zero.

As can be seen from the figure 2 the decay time is not very sensitive to the change of the wavelength between 532 and 650 nm. The difference in the current value may be explained, first of all, by different absorption coefficient values, and thus by grater overall generated charge in the case of 532 nm wavelength. Also, the average energy of the generated electron-hole pairs is higher for 532 nm wavelength. As can be seen from the figure 3, for different drain biases the decrease of the bias leads to the rise of the current decay time in the tail of current versus time dependence.

The slow decay of the drain current may be explained by the fact that generated electron and hole charges are present in the channel for a rather long time after the laser pulse is switched off. The effect may be explained, first of all, by the dynamical screening in electron-hole plasma in the transistor channel. The similar mobile charge behavior was predicted by simulations and observed in experiments in photodiodes [6]. The long current tail is mainly due to hole charge because in the case of the SOI MOSFET holes are trapped in the potential well near the $Si\text{-}SiO_2$(gate) interface for given electrode biases. Thus, generated holes are swept out of the channel much slower than electrons. It must be noted that recombination processes were not taken into account in present calculations as recombination times must be greater then the considered simulation timescales [6].

Conclusions

By means of ensemble Monte Carlo simulation the drain current response of the submicron SOI MOSFET on the picosecond pulsed laser irradiation has been investigated. For $5 \cdot 10^{10}$ W/m^2 intensity of the laser pulse it was shown that the current response represents a fast rise of approximately 1.5 ps and a rather slow decay for about 400 ps after the pulse effect. The same current behavior is observed for both wavelengths of 532 and 650 nm. The slow decay is mainly due to the generated hole charge which is swept out of the transistor channel much slower than generated electron charge.

Ensemble Monte Carlo simulation of charge carrier transport in SOI MOSFETs is a promising tool to study generated carrier dynamics under the effect of pulsed laser irradiation. Computer simulation is a good complement to real experiment and the results of simulation could be used to predict the influence of laser irradiation on the transistor electrical characteristics.

It is also possible to extend the results of the simulation to ascertain the effect of high energy particle passage through the transistor body. To do that the relationships between high energy particle characteristics and parameters of laser beam must be established. For example, some models provide relation between linear energy transfer of a particle and parameters of laser pulse [11]. The aim is to equate the number of electron-hole pairs generated by laser pulse and by the track of heavy particle in the small device region of interest. In conclusion it should be noted that laser imitation of radiation effects has some restrictions, as for example SiO_2 is transparent for considered wavelengths while heavy particle will generate charges in gate and buried SiO_2 layers. Also, the process of high power laser radiation absorption in device structures is more complex phenomenon than just fundamental single photon absorption. All these aspects must be addressed in further research and simulations of laser irradiation effects on semiconductor device structures.

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