PARTICLE-BASED SIMULATION OF ELECTRON AVALANCHE IN SILICON MICROPLASMA

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Abstract. Impact ionization was simulated in thin multiplication region ~$(0.1\div0.2)\cdot10^{-4}$ cm confined by cylinder microplasma volume with using particle-based method. Direct calculation of Coulomb repulsion between avalanche electrons is distinctive feature of this simulation. Avalanche spatial bounds were analyzed depending on angle of scattering and electric field intensity. Microplasma pulse width dependence on angle of scattering was introduced. Determined microplasma pulse width enables to evaluate dead time in random number generators.

1. Introduction

Physical noise source is a necessary part of modern random number generators. Unfortunately real source characteristics differ from ideal model ones. In this connection determination of a relation between statistical characteristics of noise and processes accompanying its generation would allow to develop sources having better characteristics.

Electron devices are used widely as physical noise sources. It is common knowledge that method of counting of randomly generated current pulses over a measured time interval and selecting a “0” or “1” according as the result is an even or odd number is fully robust with respect to long-term fluctuations of temperature and current [10]. Voltage regulator diodes, avalanche photodiodes and commercial noise diodes operated in the mode of microplasma breakdown of reverse-biased p-n-junction may be used as sources of suitable pulses. The higher pulse intensity is required the thinner depletion layer should be. Impact ionization in thin multiplication regions of state-of-the-art avalanche semiconductor devices attracts rapt attention. It makes to revise theory of charge carries multiplication [6,12].

Application of particle-based methods reveals dependence between impulse response function and physics of carrier transfer. Various models of scattering define duration and shape of impulse response function. It is familiar fact that electron bunch expands under Coulomb repulsion [3,4]. Electron bunch kinetics in external electric field in the presence of avalanche multiplication is especially interesting. Therefore we set a problem to simulate process of electron multiplication using particle-based method to determine magnitude and width of microplasma pulses.

2. Model

The software program, AVALANCHE, was developed to simulate the electron motion in an electric field with arbitrary shape and electron scattering. The program starts with a given number of initial electrons placed at chosen space points at time t=0. Electrons trajectories are then ’simultaneously’ followed in the electric field in a volume bounded by microplasma. In time interval (t, $t + dt$) each individual electron existing at time t is moved from time t to time $t + dt$ in the way, similar to [7, 9, 11] but with improvements.

The electron is moved in small and variable length time intervals t_{el}, which are fractions of dt. Before every step, the magnitude of t_{el} is calculated from the magnitude of the electric field and its gradient. In other words t_{el} must be sufficiently small in order that the vector of the electric field at the new electron’s position differs only very little from that at its original position (before t_{el}). Satisfying this requirement means, that in the time interval t_{el} the force field can be considered as unchangeable.

After every step t_{el}, the program also decides whether the electron will scatter during reaching the end of t_{el}. If the electron interacts, then first the type of the interaction is randomly chosen using the relative values for various electron-particle processes and then the interaction is simulated resulting in a change of the electron’s velocity vector. The following interactions are taken into consideration: phonon scattering and ionization. At the present time, mainly due to the lack of reliable data, an angular distribution of electron-phonon interaction is approximated by isotropic distribution. In such collisions the electron also loses energy and this is taken into account using available data [8]. Ionization collision takes place if electron accumulates sufficient energy during movement in electric field [6,12]. Then new electron is created. Its particle momentum is uniformly scattered in some spatial angle depended on gradient of electric field in the point of appearance.

When the electron finally reaches the time $t + dt$, then all new electrons created in the time interval (t, $t + dt$) in the ionization collisions and which are descendants of this electron, are moved in the same way until they all reach the time $t + dt$. At the end of every time step dt the positions and velocities of all the electrons existing at time $t + dt$ are recorded.

When the electron reaches microplasma positive side its time arrival is recorded. If electron passes through microplasma lateral surface it is lost. Simulation ends when all electrons left the microplasma volume.

So each electron free path is depicted by the combined equations taking into account nonparabolic law of dispersion

$$\hbar \frac{d\vec{k}}{dt} = -q\vec{E}(\vec{r},t) , \tag{1}$$

$$\frac{d\vec{r}}{dt} = \frac{1}{1 + 2\alpha KE(\vec{k})} \frac{\hbar \vec{k}}{m^*} , \tag{2}$$

where $\hbar$ – Planck constant, reduced; $\vec{k}$ – wave vector; q – electron charge magnitude; $\vec{E}(\vec{r},t)$ – total electric field in point $\vec{r}$ at time t; m^* – effective mass; α – nonparabolicity parameter; KE – Kinetic energy.

Electron-electron scattering is taken into account in sum vector of electric field

$$\vec{E}_i(\vec{r},t) = \sum_{j \neq i} \vec{E}_{ij}^{coul} + \vec{E}_i^{ext}(\vec{r},t) = \sum_{i \neq j} \frac{q_j}{4\pi\varepsilon\varepsilon_0} \frac{(\vec{r}_i - \vec{r}_j)}{\left|\vec{r}_i - \vec{r}_j\right|^3} + \vec{E}_i^{ext} , \tag{3}$$

where $\vec{E}_{ij}^{coul}$ and $\vec{E}_i^{ext}$ – electric field of particle j and external microscopic electric field at the center of particle i location.

Calculation of expression (3) requires huge computational burden, as application of approximation is undesirable for estimation of forces affecting on electrons because of short distances $(\vec{r}_i - \vec{r}_j) < 50$ nm and small grid spacing [5,11].

3. Simulation results

The parameters of simulated structure and experiment conditions were chosen in the following way. Impact ionization in p-silicon cylinder microplasma with height and diameter ~ $(0.1\div0.2)\cdot10^{-4}$ cm was simulated. The doping level is ~ $1\text{-}2\cdot10^{17}$ cm^{-3} [1,2]. This conditions correspond to electric field intensity ~ $(8\div4)\cdot10^5$ V/cm when avalanche breakdown occurs.

The coordinate system of simulated microplasma has been chosen such that the cylinder axis is perpendicular to the x, y plane and goes through the origin. Simulation was started after electron appeared in microplasma volume. This seeding electron might appear through the center or any other uniformly distributed point on face plane of cylinder. Solid angle of electron-phonon and impact ionization scattering were varied to investigate shape of impulse response function.

Fig. 1 shows a typical avalanche development in microplasma. We have scanned many such pictures to determine the important features. One can see that electron avalanche consists of several bunches at large values of external electric field especially (Fig. 1). It is possible to subdivide this bunches into forward, center and lagging parts. Electrons moving in front of avalanche center have the largest group speed and electrons, which are in back of avalanche center, have the least one. This electron distribution arises from Coulomb repulsion and results in avalanche pulse width spreading. Perhaps increase of avalanche spatial bounds is because of scattering spatial angle as well. It should be noted that multiplication factor is depends on scattering angles. The larger scattering angles the less multiplication factor (Fig. 1a, Fig. 1c).

Average impulse response function depending on scattering angle for $E^{ext} = 5\cdot10^5$ V/cm is introduced in Fig 2. One can see that scattering angle effects on time of avalanche arrival to positive side of microplasma and smoothes over the spatial desintegration of electron bunch.

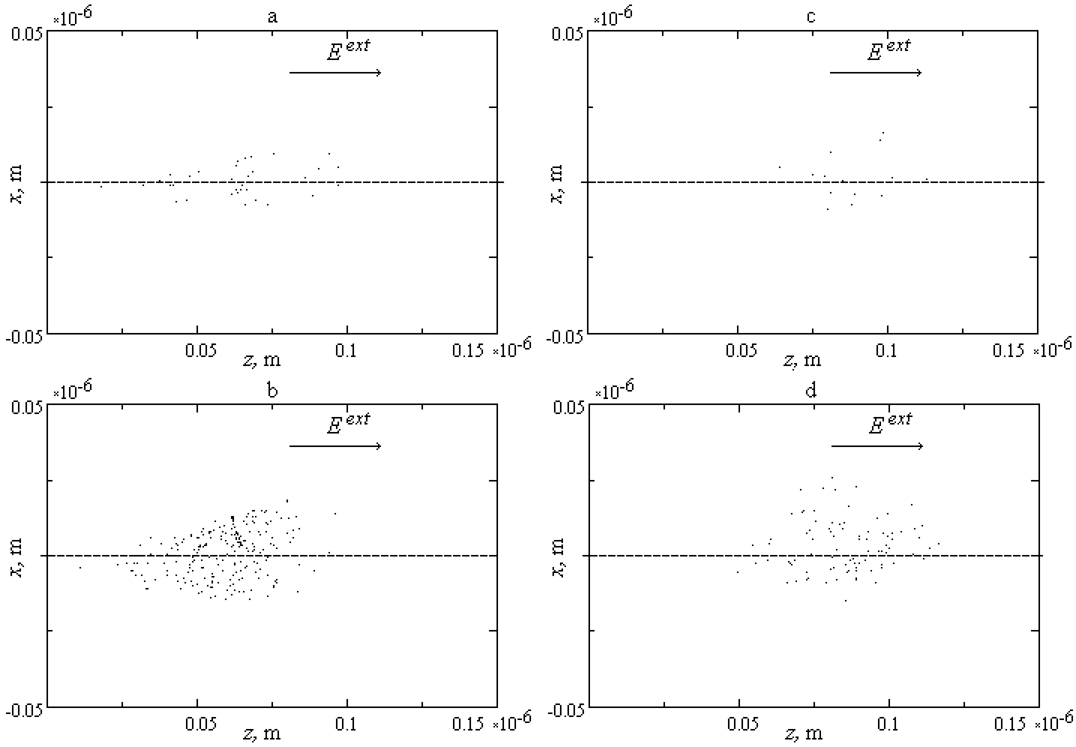

Fig. 1. Instantaneous snap-shots of electron positions for various external electric field and scattering angles: a – $E^{ext} = 5 \cdot 10^5$ V/cm, α=5°; *b –* $E^{ext} = 7 \cdot 10^5$ V/cm, α=5°; *c –* $E^{ext} = 5 \cdot 10^5$ V/cm, α=90°; *d –* $E^{ext} = 7 \cdot 10^5$ V/cm, α=5°.

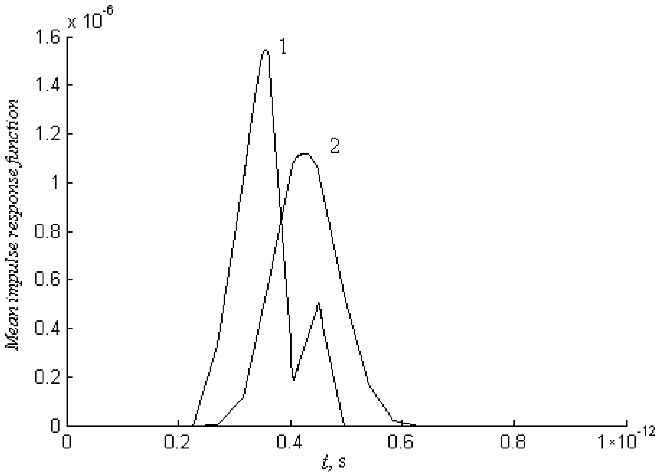

Fig. 2. Mean impulse response function for various scattering angles ($E^{ext} = 5 \cdot 10^5$ V/cm): *1 –* α=5°; *2 –* α=90°.

The results of simulation show that effect of electron avalanche desintegration on bunches becomes apparent more obviously under small angles of electron-phonon and impact ionization scattering because of large Coulomb forces of charge carriers moving at a short distance one after the other.

4. Conclusions

Application of particle-based method requires huge computational burden but it gives an opportunity to follow on the each particle trajectory. Appointed impulse response function dependencies will be used in random number generator utilizing the method of random pulse counting. Further investigation of avalanche development process in presence of several seeding electrons is of future interest. This investigation will enable to evaluate dead time distortions introduced in initial seeding process.

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