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INTERNAL AMPLIFICATION OF CURRENT PULSES INSIDE A REVERSE-BIASED PNIPN-STRUCTURE

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Abstract

We present computer simulations for a model of a nonlinear device, which in previous work we suggested to detect the passage of high-energy particles by measuring current oscillations having frequency larger than the frequency of successive events. The aim is to show that the device proposed can indeed perform the task for which it was designed.

Key Words

Multilayered semiconductor structure, drift-diffusion model, HEP detector, spatiotemporal dynamics

1. Introduction

Multiple amplification due to impact ionization inside pn-junctions occurs in reverse-biased pnipn-structure devices, which give rise to current oscillations, have recently been studied in [1, 2]. Applications of such structures for the design of high-energy particle detectors, and in particular, semiconductor photoelectron multipliers, have been suggested in [1], and the authors of [2] show that this structure could be used for chaotic waveform generator design. In those articles the analysis of spatiotemporal dynamics of the currents inside the reverse-biased pnipn-structure was carried out with the help of a simplified model, which is constructed within the framework of a phenomenological approach. The device studied is the semiconductor structure, consisting of two pn-junctions, connected through an intrinsic semiconductor and brought close to, rather than exceeding, the avalanche breakdown limit via reverse-bias voltage. Two depletion slabs with a low conductivity arise in the neighbourhood of these junctions due to the reverse-bias voltage applied. The conductivity of the intrinsic region will be much larger than that of the depletion, and the distribution of the electric field (E-field) strength across this structure will have two peaks around the physical pn-junctions.

Therefore, in the structure described above, conditions can exist such that in the neighbourhoods of the junctions there will be an E-field strength large enough to be close to its value for avalanche threshold (but will not exceed it), and at the same time it will be much lower than the field in the intrinsic region. This means that the impact ionization will take place only inside the slabs. This impact ionization produces two clouds of charges: holes and electron ones. The electrons generated move from left to right, and holes move in the reverse direction. The E-field inside the intrinsic region is not large enough to provide hole–electron pairs generation, so the electrons just generated will reach the second slab and, being accelerated by the local E-field, will cause another impact ionization. Now, the cloud of holes will move towards the first depletion slab without changing inside the i-region and will induce the next charge multiplication via impact ionization inside the first slab, and so on.

Thus, current oscillations can exist in this structure due to successive transformation of the electrons (holes) pulses into the holes (electrons) at the narrow depletion slabs and their propagation through the intrinsic region. We introduced a simplified model for this process that enables us to reduce the initial-boundary problem for partial differential equations of drift-diffusion model presented in [1, 2] to that of the much simpler mathematical object: a difference equation (DE) or difference-delay equation (DDE). The boundary conditions have been obtained within the frame of a phenomenological approach using charge multiplication due to impact ionization inside the depletion slabs. In the general case of different mobility, the primary problem is reduced to coupled nonlinear DE or DDE. In the case of symmetric junctions, the problem under consideration is reduced to two independent DE or DDE. The evolution of the initial current pulse (produced by a high-energy particle, for instance) is studied for different combinations of the device parameters. It is shown in [1] that it is possible to obtain an oscillatory-like response of

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the considered structure after the passage of a high-energy particle, when the reverse-bias voltage does not exceed the avalanche breakdown threshold. This regime provides an internal amplification of the initial current pulse produced by a particle.

However, in order to have a complete, self-consistent, description of the structure under consideration and to obtain a reliable evaluation of its performance, we need to make numerical simulations of a more realistic model.

In Section 2, we present the model of the device. In Section 3 we describe the numerical simulations, and in Section 4 we carry out numerical simulations of the above regimes in order to justify the results obtained in [1, 2] within the frame of the drift-diffusion model.

2. The Model

The semiconductor pnipn-structure (Fig. 1) considered here consists of five layers that form two external pn-junctions and one internal nip-junction. The external p1- and n2-layers have a higher-impurity doping while the middle n1- and p2-regions are rather weakly doped. The profile of the doping inside the junctions corresponds to the so-called abrupt pn-junction with a step-like approximation for the distribution of impurities. This approximation adequately describes the alloyed, fine diffusion, and ion-implanted pn-junctions [3].

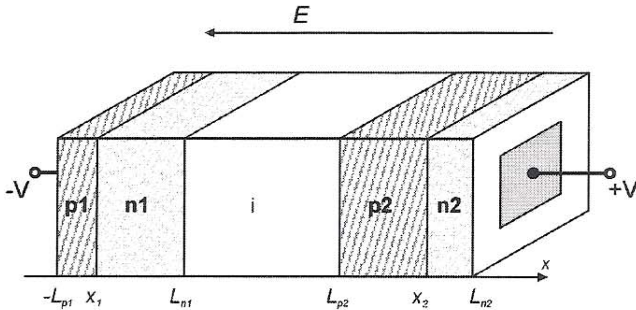

Figure 1. Schematic of the semiconductor pnipn-structure.

Under the reverse-bias voltage applied across the pnipn-structure ("−" refers to the p1-region and "+" to the n2-region) the p1n1- and p2n2-junctions are connected in the opposite direction, and the n1ip2-junction is connected in the direct one. Two depletion slabs with low conductivity arise in the neighbourhoods of the pn-junctions due to the reverse-bias voltage applied. The strength of this field does not exceed its threshold value at which the avalanche breakdown starts, but it is sufficiently large for the existence of impact ionization inside the depletion layers of the pn-junctions. At the beginning, the initial pulse of electrons is injected into the multiplication area of the p1n1-junction, where the impact ionization produces multiplication of the electrons. After that, the electron current pulse flows out of the p1n1-junction and moves into the i-region. The constant E-field of the i-region forces this pulse to move with a constant velocity towards the p2n2-junction. In the multiplication layer of this junction the charge carriers are multiplied again due to impact ionization. Now, the pulse of holes current flows out of the p2n2-junction and moves into the i-region, and keeps moving with a constant velocity towards the first p1n1-junction. Flying into the multiplication layer of this junction, the holes current induces impact ionization and, as a result, the number of charge carriers increases again. Thus, the number of pulses and their amplitude grow with time. This process can be stopped, cancelling the reverse biasing of the structure. The train of pulses generated will be used to extract information on the initial parameters of the pulse.

The basic equations of the drift-diffusion model describe both the static and the dynamic behaviour of the charge carriers inside the semiconductor structure under the effect of external fields. For a one-dimensional semiconductor structure with uniformly doped pn-junction as shown in Fig. 1, those equations take the form [4]:

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon\varepsilon_0}(p - n + N); \quad E = -\frac{\partial \varphi}{\partial x} \tag{1}$$

$$\begin{aligned} \frac{\partial n}{\partial t} &= -\frac{1}{q}\frac{\partial J_n}{\partial x} - R + \alpha_n J_n + \alpha_p J_p \\ \frac{\partial p}{\partial t} &= \frac{1}{q}\frac{\partial J_p}{\partial x} - R + \alpha_n J_n + \alpha_p J_p \end{aligned} \tag{2}$$

$$\begin{aligned} J &= J_n + J_p + J_{dis}; \quad J_{dis} = \varepsilon\varepsilon_0 \frac{\partial E}{\partial t} \\ J_n &= qnv_n; \quad J_p = qpv_p \\ R &= \frac{pn - n_i^2}{\tau_n(p + p^*) + \tau_p(n + n^*)} \end{aligned} \tag{3}$$

Here E is the E-field; n_i is the electron concentration for the intrinsic (non-doped) semiconductor; $\varepsilon\varepsilon_0$ is the dielectric constant of the semiconductor; $N(x) = N_d - N_a$, with N_d and N_a being the concentrations of the ionized donor and acceptor atoms, respectively; J_n and J_p are the electron and hole current densities, respectively; J_{dis} is the displacement current density; t is the time and x is the spatial coordinates; n is the concentration of electrons; p is the concentration of holes; q is the electron charge magnitude; R is the rate of the electron–hole pair generation (recombination) for the Shockley–Hall–Read model [3]; τ_n and τ_p are, respectively, the electron and hole lifetimes; and α_n and α_p are the impact ionization rates for electrons and holes, respectively.

For the sake of simplicity, let us reduce (1) through (3) to a dimensionless form. To that end, we will introduce the following dimensionless variables: $\hat{E} = E/E_0$; $\hat{\varphi} = \varphi/\varphi_0$; $\hat{n} = n/n_i$; $\hat{p} = p/n_i$; $\hat{N} = N/n_i$; $\hat{x} = x/L_0$; $\hat{t} = t/t_0$; $\hat{\tau}_n = \tau/t_0$; $\hat{\tau}_p = \tau/t_0$; $\hat{j}_n = j_n/j_0$; $\hat{j}_p = j/j_0$; $\hat{j}_{dis} = j_{dis}/j_0$.

The normalizing factors are: $E_0 = \varphi_0/L_0$ [V m^{-1}]; $D_0 = 1$ [m^2 s^{-1}]; $L_0 = \sqrt{\varepsilon\varepsilon_0\varphi_0/qn_i}$ [m]; $t_0 = L_0/D_0$ [s]; and $J_0 = qn_iD_0/L_0$ [A m^{-2}].

Upon some manipulation and normalization, (1) through (3) can be rewritten in the dimensionless form

(hereinafter, the cap "^" will be omitted for simplicity):

$$\frac{\partial E}{\partial x} = N(x) + p - n; \quad E = -\frac{\partial \varphi}{\partial x}, \tag{4}$$

$$\begin{aligned} \frac{\partial n}{\partial t} &= -\frac{\partial J_n}{\partial x} - R + \alpha_n J_n + \alpha_p J_p \\ \frac{\partial p}{\partial t} &= \frac{\partial J_p}{\partial x} - R + \alpha_n J_n + \alpha_p J_p \end{aligned} \tag{5}$$

$$\begin{aligned} J_n &= v_n n; \quad J_p = v_p p; \quad J_{dis} = \frac{\partial E}{\partial t} \\ J &= J_n + J_p + J_{dis} \end{aligned} \tag{6}$$

For the case of identical impact ionization rates for electrons and holes $\alpha_n = \alpha_p = \alpha$, the full current density J can be found from the equation below, which follows from (4)–(6):

$$\begin{aligned} \frac{L}{v}\frac{dJ}{dt} &= J_s - J\left(1 - \int_{-L_p}^{L_n} \alpha(E)\, dx\right) \\ &+ \frac{1}{v}\frac{d^2V}{dt^2} - \int_{-L_p}^{L_n} \alpha(E) J_{dis}(x)\, dx \end{aligned} \tag{7}$$

where $v = v_n + v_p$; $J_s = J_{sn} + J_{sp}$ is the total saturation current density where $J_{sn} = n_i D_n / L_d$, $J_{sp} = n_i D_p / L_a$ are the densities of electron and hole saturation currents; and D_n and D_p are diffusion coefficients of electrons and holes, respectively.

For the p1n1-junction, the charge carriers' multiplication rate is defined by the formula $M_1 = 1/(1 - \int_{-L_{p1}}^{L_{n1}} \alpha(E)\, dx)$, and the avalanche threshold voltage is determined from the avalanche breakdown condition: $1 - \int_{-L_{p1}}^{L_{n1}} \alpha(E)\, dx = 0$ [3]. For the p2n2-junction, both the avalanche threshold voltage and the multiplication rate are defined in a similar way.

3. Initial and Boundary Conditions

For a self-consistent description of the spatiotemporal dynamics of the currents in the system under consideration, we have to prescribe a proper number of initial and boundary conditions. In order to do that we divide the entire problem into two different stages. In the first stage, it is necessary to calculate the distribution of the static E-field and the potential across the pnipn-structure after the reverse-bias voltage has been applied. At this stage, the description of the system is reduced to solving the Poisson equation for a given charge distribution across the pnipn-structure, which will give us distributions of the inserted field and potential. This solution is rather simple. It shows the existence of a stable two-peak distribution of the E-field required for our purposes. We assume that this distribution is known and beyond our current interest. The required E-field amplitudes as well as the sizes L_{n1} and L_{p1} of the depletion layers around p1n1-junctions and sizes L_{p2} and L_{n2} of the depletion layers around p2n2-junctions can be provided by an appropriate choice of the doping rates, doping areas sizes, and reverse-bias voltage applied. It is well known that increasing the reverse-bias voltage will widen the depletion area in a pn-junction, until it reaches the contacts. Similar processes take place in both pn-junctions of the pnipn-structure under consideration. This means that for asymmetrical pn-junctions the variation of the sizes of the p and n areas, their doping rates and the reverse-bias voltage applied, will allow a change of the electric charge in those junctions and, hence, the E-field in the i-region. For instance, when in the p1n1-junction the acceptors charge, Q_a^1, is greater than the donors charge, Q_d^1, whereas in the p2n2-junction, the acceptors charge, Q_a^2, is smaller than the donors charge, Q_d^2, the p1n1-junction will have the total charge $Q_1 = Q_a^1 - Q_d^1$, and the p2n2-junction will have the charge $Q_2 = Q_a^2 - Q_d^2$. This charge in the pn-junctions will create an E-field in the i-region. For the case of uniform and equal doping rates and sizes, this field is: $E_i = N_a^1(L_{p1} - L'_{p1}) = N_d^2(L_{n2} - L'_{n2})$.

Then, the required boundary conditions can be written as follows:

$$\begin{aligned} \varphi(-L_{p1}) &= V - \ln(N_{a1}) \\ \varphi(L_{n1}) &= (V - V_i - V_2) - \ln(N_{d1}) \\ \varphi(L_{p2}) &= V_2 - \ln(N_{a2}) \quad \varphi(L_{n2}) = \ln(N_{d2}) \\ J_p(-L_{p1}) &= J - J_{n0} \quad J_n(L_{n1}) = J - J_{pi} \\ J_p(L_{p2}) &= J - J_{ni} \quad J_n(L_{n2}) = J - J_{p0} \\ \varphi(x_i - 0) &= \varphi(x_i + 0) \\ \left.\frac{\partial \varphi(x,t)}{\partial x}\right|_{x=x_i-0} &= \left.\frac{\partial \varphi(x,t)}{\partial x}\right|_{x=x_i+0} \end{aligned} \tag{8}$$

Here, x_i, $i = 1, 2$ is the coordinate of the interface between the p- and n-regions; $V = V_1 + V_i + V_2$, V is the voltage across the pnipn-structure; V_1 and V_2 are the voltages across the p1n1- and p2n2-junctions, respectively, and V_i is the voltage across the i-area; J_{n0} and J_{p0} are the densities of electron and hole saturation currents, respectively; J_{pi} and J_{ni} are the densities of the electron and hole currents flowing into the p1n1- and p2n2-junctions from the i-area at the initial times, respectively; and $L = L_{n1} + L_{p1}$ is the width of a depletion region of the p1n1-junction.

In addition, the above static equations give the following formulae:

$$J = J_s \Big/ \left(1 - \int_{-L_p}^{L_n} \alpha(E)\, dx\right) \tag{9}$$

$$\begin{aligned} J_n &= J_s + J\int_x^{L_n} \alpha(E)\, dx \\ J_p &= J_s + J\left(\int_{-L_p}^{L_n} \alpha(E)\, dx - \int_x^{L_n} \alpha(E)\, dx\right) \end{aligned} \tag{10}$$

which serve as the initial conditions for (5) and (6) when no external forces act on the pnipn-structure.

4. Spatiotemporal Behaviour

The second stage in solving the problem is the calculation of the spatiotemporal evolution of the initial current pulse using (4)–(7), boundary conditions (8), and initial conditions (9) and (10). The solution for the initial-boundary

value problem, (4)–(10), is performed numerically with the help of the modified counter-sweep method [4]. We show how the method works, applying it to the p1n1-junction (hereinafter the subscript "1," defining all the variables for this junction, is omitted). Let us introduce in the area $G\{-L_p \le x \le L_n;\ 0 \le t \le T\}$ a non-uniform mesh:

$$\omega_{h\tau} = \{(x_i, t^j),\ x_{i+1} = x_i + h_i,\ i = 2, 3, \ldots, M-1;\\ t^{j+1} = t^j + \tau,\ j = 1, 2, \ldots, N\}$$

where h_i is the coordinate step and τ is the time step. The time step τ should be smaller of each time of flight across the i-region by both electrons and holes. We attribute the mesh function U_i^j to the mesh nodes (x_i, t^j). Substitution of the differential operators in (4)–(6) by their difference analogues according to [4] gives the following semi-implicit difference scheme:

$$A_{\varphi_i}\varphi_{i-1}^{j+1} - C_{\varphi_i}\varphi_i^{j+1} + B_{\varphi_i}\varphi_{i+1}^{j+1} = -F_{\varphi_i}^j \qquad (11)$$

$$J_{ni+1}^{j+1} = A_{ni}J_{ni}^{j+1} + \frac{h}{v_n\tau}J_{ni}^j + h\alpha_i^{j+1}(J^{j+1} - J_{dis\,i}^{j+1})$$

$$J_{pi+1}^{j+1} = A_{pi}J_{pi}^{j+1} - \frac{h}{v_p\tau}J_{pi}^j - h\alpha_i^{j+1}(J^{j+1} - J_{dis\,i}^{j+1}) \qquad (12)$$

$$J^{j+1} = A_j\left(J^j + \frac{v\tau}{L}\left(J_s + \frac{V^{j+1} - 2V^j + V^{j-1}}{v\tau^2} - \int_{-L_p}^{L_n}\alpha(x)J_{cm}(x)\,dx\right)\right) \qquad (13)$$

where:

$$A_{\varphi_i} = \frac{1}{h_i^2} \quad B_{\varphi_i} = A_{\varphi_i} \quad C_{\varphi_i} = 2A_{\varphi_i}$$

$$F_{\varphi_i}^j = N_i + p_i^j - n_i^j$$

$$A_j = 1\Big/\left(1 + \frac{v\tau}{L}\left(1 - \int_{-L_p}^{L_n}\alpha(x)\,dx\right)\right)$$

$$A_{ni} = 1 - \frac{h_i}{v_n\tau} \quad A_{pi} = 1 + \frac{h_i}{v_p\tau}$$

The DEs (11)–(13) form a set of the algebraic equations with tridiagonal matrix. First, we find, in a straightforward manner, solutions for the DE (11) using this explicit formula and initial distributions for electron and hole densities. The evaluation will be carried out as follows: for the time layer $t = \tau$, from the DE (11), the analogue of Poisson's equation (4), we determine the E-field strength neglecting the influence of electrons and holes on the E-field. Then, from the stationary equations (9) and (10), we evaluate the electron and hole current densities caused by impact ionization in the p1n1-junction, which are used as the initial conditions for (12) (the difference analogue of (5) and (6)). Solving those equations, we find the full electron and hole currents densities for the next temporal layer $t = 2\tau$. These values, along with the E-field strength and the potential found before, are used as initial conditions to calculate the solution for the next temporal layer $t = 3\tau$, and so on. The solutions for the p2n2-junction are evaluated in a similar way. The terms responsible for the impact are omitted when we solve (12) for the i-region.

Having solutions for each region separately, we have the possibility to obtain the spatiotemporal behaviour of the current and charge densities in the following way: let us consider the case when initially only an electron current impulse is injected into the p1n1-junction. Using the time dependence of this pulse as an initial condition for the DEs (11)–(13), we define the electron current density flowing out of the p1n1-junction. This value is used as the initial condition for the same equations to find the currents flowing out of the i-region. After that, we repeat the first step, but for the p2n2-junction. It should be noticed that in this case we are interested in the holes current dependency flowing out of the p2n2-junction into the i-region, and we take this dependence as the initial conditions for holes current density propagating through the i-region towards the p1n1-junction. This procedure is to be repeated at each time step. In this way, instead of solving an initial-boundary-value problem for the pnipn-structure as a whole system, we use the procedure of matching the input and output currents at the interfaces.

5. Numerical Simulations and Discussion

We carry out the numerical calculations for three pnipn-structures manufactured on the basis of different semiconductors, namely, silicon, gallium arsenide, and germanium. All related plots are labelled Si, GaAs, and Ge, respectively.

The pnipn-structures under consideration have the main parameters listed in Table 1.

We use the exponential approximation for the dependency of the impact ionization rates on the E-field [3]: $\alpha(E) = A\exp[-(b/E)]^m$. The constants A, m, and b are defined in Table 2.

The constants of the DEs scheme will be chosen according to the method suggested in [4]. For instance, those parameters for silicon are as follows:

$$\tau = 0.12 \times 10^{-8}\,[\mathrm{s}] \quad h_p = 0.547 \times 10^{-7}\,[\mathrm{cm}]$$
$$h_n = 0.547 \times 10^{-6}\,[\mathrm{cm}] \quad h_i = 0.32 \times 10^{-5}\,[\mathrm{cm}]$$

The values of the normalization factors for each semiconductor are given in Table 3.

In Fig. 2 we present the results for the solution of the static problem (4) and (8). The distribution of the potential (upper row), E-field (middle row), and doping rates (lower row) across the pnipn-structure is shown in Figs. 2(a–c) for silicon, gallium arsenide, and germanium, respectively.

It is worth noting that inside the i-region of the pnipn-structure there is a constant E-field that, in our case, is much smaller than the field inside the pn-junctions. The presence of that field enables electrons and holes to move through the i-region in mutually opposite directions. The values of the E-field and drift velocities are given in Table 4.

This motion of electrons and holes creates drift currents flowing through the i-region, which provide positive delay feedback between the pn-junctions, where impact ionization generates the electron–hole pairs.

In the case of zero E-field inside the i-region, the positive feedback can exist due to diffusion currents. This regime will not be considered in the present work.

Table 1
Main Parameters of the pnipn-Structures

Parameter	Semiconductor		
	Si	GaAs	Ge
Dielectric constant, ε	11.9	10.9	16
Intrinsic concentration of charge carriers, n_i (cm^{-3})	1.6×10^{10}	1.1×10^7	2.5×10^{11}
Size of the i-region, $d_i = L'_{p2} - L'_{n1}$ (μm)	1.04	0.83	0.91
Size of the p1- and n2-regions, $x_1 - L'_{p1}$ and $L'_{n2} - x_2$ (μm)	0.202	0.228	0.199
Size of the n1- and p2-regions, $L'_{n1} - x_1$ and $x_2 - L'_{p2}$ (μm)	2.02	2.281	1.985
Doping rates of the narrow layers, $N_{a1} = N_{d2}$ (cm^{-3})	10^{17}	10^{17}	10^{17}
Doping rates of the wide layers, $N_{d1} = N_{a2}$ (cm^{-3})	10^{16}	10^{16}	10^{16}
Electrons mobility, μ_n ($cm^2\,s^{-1}\,V^{-1}$)	1,500	8,500	3,900
Holes mobility, μ_p ($cm^2\,s^{-1}\,V^{-1}$)	600	400	1,900
Saturation velocity of electrons, v_{sn} ($cm\,s^{-1}$)	10^7	10^7	6×10^6
Saturation velocity of holes, v_{sp} ($cm\,s^{-1}$)	0.5×10^7	0.5×10^7	3×10^6

Table 2
Constants for the Avalanche Ionization Coefficient Approximation [3]

Parameter	Semiconductor		
	Si	GaAs	Ge
A (cm^{-1})	3.8×10^6	3.5×10^5	1.5×10^7
b ($V\,cm^{-1}$)	1.75×10^6	6.85×10^5	1.56×10^6
m	1	2	1

Table 3
Normalization Factors

Parameter	Semiconductor		
	Si	GaAs	Ge
L_0 (cm)	0.326×10^{-2}	0.119	0.956×10^{-3}
t_0 (s)	0.106×10^{-8}	0.141×10^{-5}	0.91×10^{-10}
J_0 ($A\,cm^{-2}$)	78.5×10^{-4}	1.48×10^{-7}	0.42

In [1, 2] we studied the regime of current oscillations in the pnipn-structure due to a cyclic pulse amplification of the drift currents, with a phenomenological approach. Here, we study this regime numerically. Assume that at the time $t = \tau_0$ the pulse of electrons is injected into the multiplication layer of the p1n1-junction having a Gaussian time distribution: $J_n(-L'_p, t) = J_{n0} \exp^{[-(t-\tau_0)^2/\beta^2]}$. Here the parameter β defines the initial current pulse width ($1/\beta << (L'_{p2} - L'_{n1})/v_p$). The pulse amplitude should exceed not only the level of the thermal noise, but also the amplitude of the total saturation current.

As a result of the successive multiplication of charge carriers due to impact ionization inside the reverse-biased junctions described previously, the currents produced have the time-dependency shown in Figs. 3(a–c) for the field distributions of Figs. 2(a–c), respectively. From Fig. 3 it can be seen that the previous phenomenological model is quite adequate to describe the complete solution, which has been numerically simulated here. That is, if the reverse-bias voltage does not exceed the value of the avalanche breakdown threshold, the amplification of the initial electron pulse due to impact ionization takes place inside the pn-junctions. After that, the first electron pulse is injected into the i-region. It reaches the p2n2-junction after a time delay $t_n = d_i/\bar{v}_n$ (where d_i is the width of the i-region and $\bar{v}_n$ is the average drift velocity of electrons). Inside this junction, the multiplication of charge carriers due to impact ionization takes place again. As a result, the pulse of holes is injected into the i-region that, after a time delay $t_p = d_i/\bar{v}_p$ ($\bar{v}_p$ is the average drift velocity of holes), reaches the p1n1-junction. Inside this junction, the multiplication of charge carriers due to impact ionization takes place again. The second electrons pulse is injected into the i-region, and the same process described is repeated indefinitely. One can see up to three pairs of the current pulses for silicon and germanium in Figs. 3(a) and (c), whereas for gallium arsenide in Fig. 3(b) there are four single pulses. This is due to the big difference between the drift velocities of electrons and holes for gallium arsenide (Table 4). For the constants used in the DEs for GaAs, it is impossible to resolve the electron and hole contributions in the full current.

The spatiotemporal pattern of the motion of the charge carriers inside the i-region is shown in Fig. 4 for all three semiconductors under consideration. The pulse of electrons moves in the positive direction of the X-axis at a given velocity. The pulse of holes moves in the negative

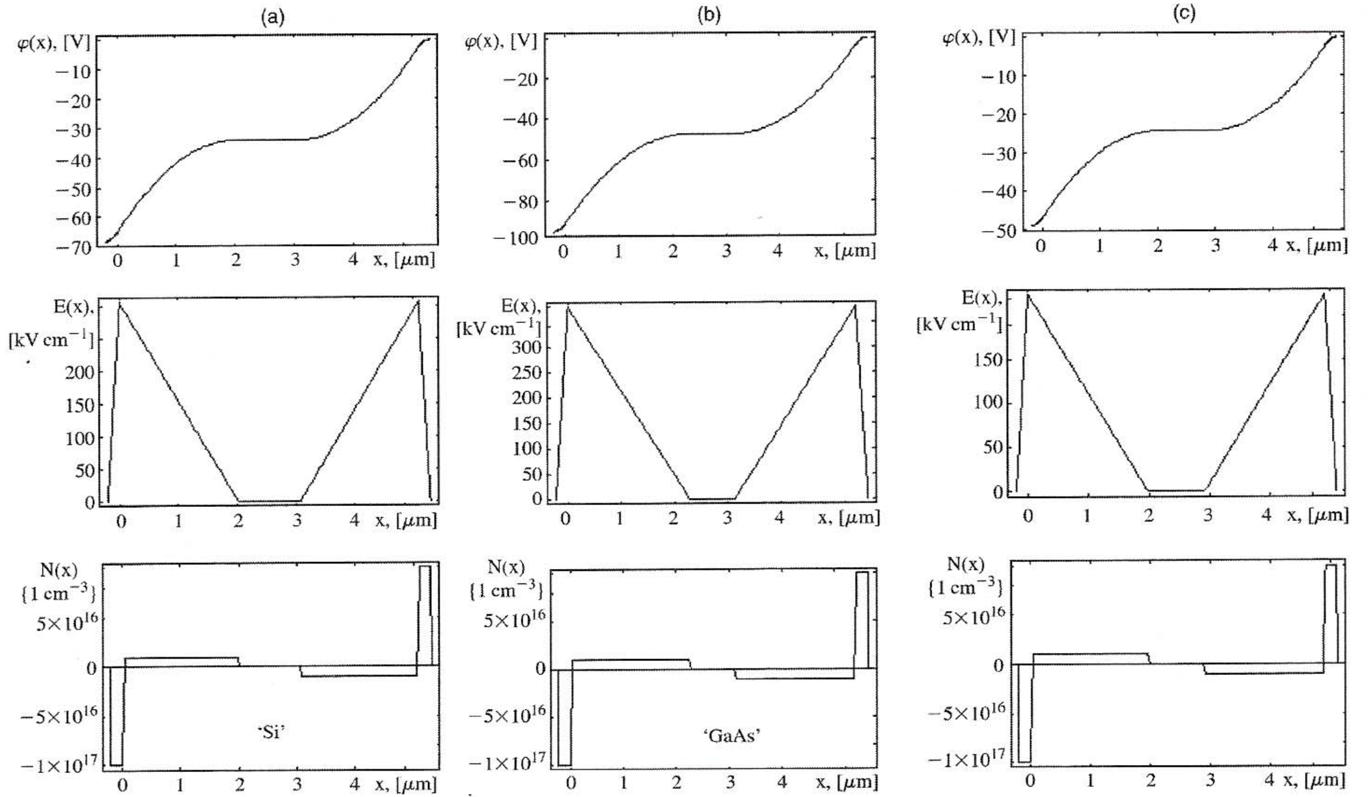

Figure 2. Distribution of potential (upper row), electric field (middle row), and doping rate (lower row) for three semiconductor materials, across the pnipn-structure. (a) Silicon (Si): $N_{a1} = 10^{17}\,\mathrm{cm}^{-3}$; $N_{d1} = 10^{16}\,\mathrm{cm}^{-3}$; $N_{a2} = N_{d1}$; $N_{d2} = N_{a1}$; $n_i = 1.6 \times 10^{10}\,\mathrm{cm}^{-3}$. (b) Gallium Arsenide (GaAs): $N_{a1} = 10^{17}\,\mathrm{cm}^{-3}$; $N_{d1} = 10^{16}\,\mathrm{cm}^{-3}$; $N_{a2} = N_{d1}$; $N_{d2} = N_{a1}$; $n_i = 1.1 \times 10^{7}\,\mathrm{cm}^{-3}$. (c) Germanium (Ge): $N_{a1} = 10^{17}\,\mathrm{cm}^{-3}$; $N_{d1} = 10^{16}\,\mathrm{cm}^{-3}$; $N_{a2} = N_{d1}$; $N_{d2} = N_{a1}$; $n_i = 2.5 \times 10^{11}\,\mathrm{cm}^{-3}$.

Table 4
E-Field and Drift Velocities inside the i-Region

Parameter	Semiconductor		
	Si	GaAs	Ge
E-field inside i-region, E_i ($\mathrm{V\,cm}^{-1}$)	3.21	2.89×10^{-3}	10.49
Electron drift velocity, v_{sn} ($\mathrm{cm\,s}^{-1}$)	4.212	24.6	40.900
Hole drift velocity, v_{sp} ($\mathrm{cm\,s}^{-1}$)	1.925	1.16	19.900

direction with a very different value. The amplitudes of those propagating currents are constant as the recombination/relaxation processes are not taken into account. The consequence of the amplification process due to the impact ionization inside the depletion layers is clearly seen, namely, the current amplitudes are enlarged in the neighbourhoods of the pn-junctions according to the multiplication rates. We can also see from Fig. 4 that the electrons and holes pulses cannot mutually recombine in the major part of the i-region, because in that area they are flying alternately. At the same time, near the pn-junctions there is a non-zero probability of their direct recombination as the flux of electrons and holes are present simultaneously.

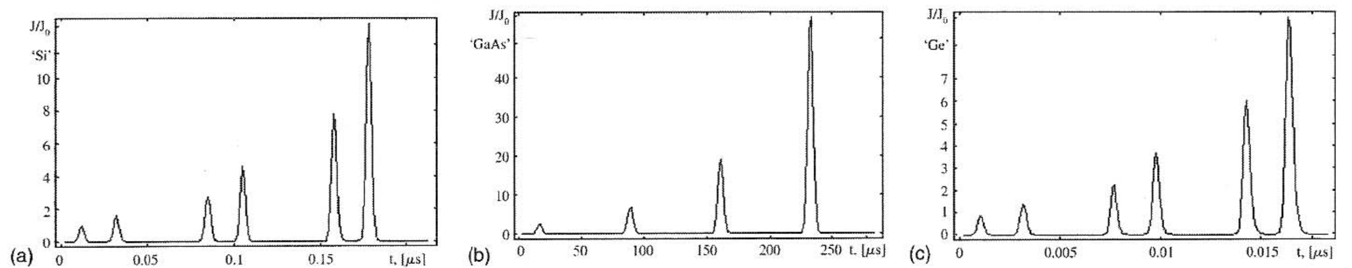

Figure 3. Time dependence of the total current density flowing through the i-region for the pnipn-structures given in Fig. 2. (a) Silicon (Si): the pn-junctions have multiplication rates $M1 = M2 = 1.63$; total current density $J_0 = 78.5\,\mathrm{A\,m}^{-2}$. (b) Gallium Arsenide (GaAs): the pn-junctions have multiplication rates $M1 = M2 = 1.6$; total current density $J_0 = 1.48\,\mathrm{mA\,m}^{-2}$. (c) Germanium (Ge): the pn-junctions have multiplication rates $M1 = M2 = 1.61$; total current density $J_0 = 4.185\,\mathrm{kA\,m}^{-2}$.

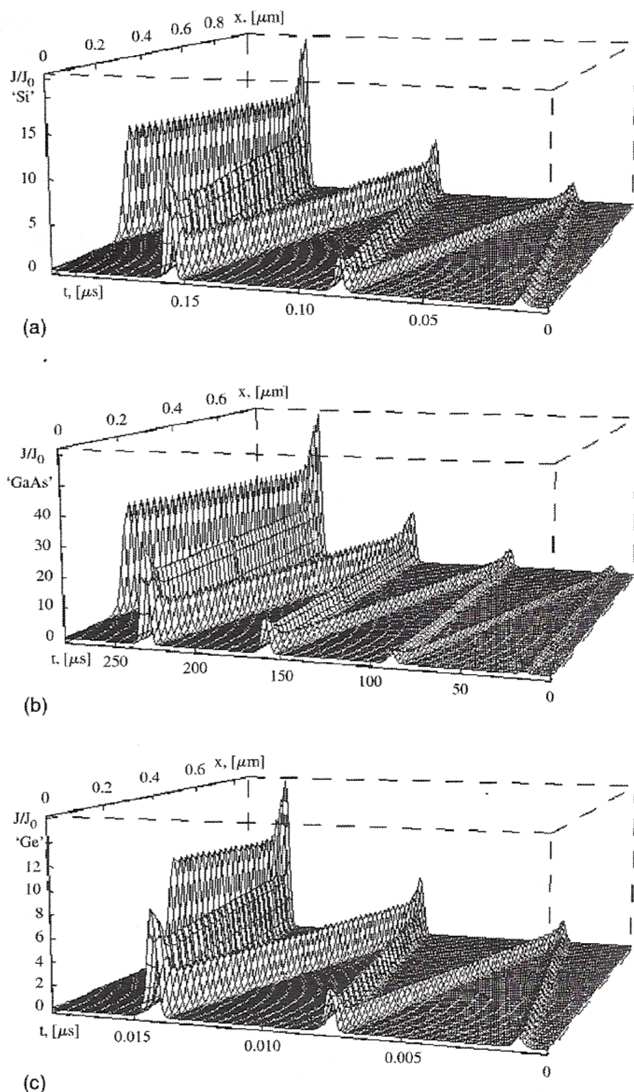

Figure 4. Spatio-temporal patterns of the total current density inside the i-region of the pnipn-structure for the parameters used in Figs. 2 and 3. (a) Silicon (Si): electric field in the i-region $E_i = 3.21\,\mathrm{V\,cm^{-1}}$; electron drift velocity in the i-region $v_{ni} = 0.042\,\mathrm{m\,s^{-1}}$; hole drift velocity in the i-region $v_{pi} = 0.019\,\mathrm{m\,s^{-1}}$; multiplication rates $M1 = M2 = 1.63$; total current density $J_0 = 78.5\,\mathrm{A\,m^{-2}}$. (b) Gallium Arsenide (GaAs): electric field in the i-region $E_i = 2.89\,\mathrm{mV\,cm^{-1}}$; electron drift velocity in the i-region $v_{ni} = 0.246\,\mathrm{m\,s^{-1}}$; hole drift velocity in the i-region $v_{pi} = 0.0116\,\mathrm{m\,s^{-1}}$; multiplication rates $M1 = M2 = 1.6$; total current density $J_0 = 1.48\,\mathrm{mA\,m^{-2}}$. (c) Germanium (Ge): electric field in the i-region $E_i = 10.49\,\mathrm{V\,cm^{-1}}$; electron drift velocity in the i-region $v_{ni} = 0.04\,\mathrm{m\,s^{-1}}$; hole drift velocity in the i-region $v_{pi} = 0.199\,\mathrm{m\,s^{-1}}$; multiplication rates $M1 = M2 = 1.61$; total current density $J_0 = 4.185\,\mathrm{kA\,m^{-2}}$.

6. Conclusion

In this article we have shown, using an adequate model and numerical technique, that the pnipn semiconductor structure can efficiently detect the passage of a high-energy particle. It was already suggested in [1] that this type of device could produce oscillations that were of much shorter period than the time between events. With the simulations presented here we see that those oscillations indeed appear in this type of device. It is now clear that the device can perform the task for which it was designed.

Acknowledgement

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References

[1] K.A. Lukin, H.A. Cerdeira, & A.A. Colavita, Current oscillations in avalanche particle detectors with pnipn-structure, *IEEE Transactions on Electron Devices*, *43*(3), 1996, 473–478.

[2] K.A. Lukin, H.A. Cerdeira, & A.A. Colavita, Chaotic instability of currents in a reverse biased multilayered structure, *Applied Physics Letters*, *71*(17), 1997, 2484–2486.

[3] S.M. Sze, *Physics of semiconductor devices* (New York: Wiley-Interscience, 1981).

[4] K.A. Lukin & P.P. Maksymov, A method for evaluating of semiconductor structure with abrupt pn-junction, *Radiophysics and Electronics*, *4*(1), 1999, 87–92.

Biographies

Konstantin A. Lukin received the Diploma-Engineer degree in 1973 from Kharkov State University, Ukraine, USSR. Since 1973 he has been with the Institute of Radiophysics and Electronics, National Academy of Sciences of Ukraine, Kharkov. He received his Candidate of Sciences (mathematics and physics) degree in 1980 from Moscow State University, and the Doctor of Sciences (mathematics and physics) degree in 1989 from Kharkov State University. Both dissertations were devoted to theory of nonlinear processes in millimeter-wave vacuum electron devices. He is author and co-author of more than 60 journal publications in this field. His current research interests are nonlinear dynamics of various physical systems with delay feedback, and generation and processing of chaotic/noise waveforms and their applications. Currently his main activities lie in the field of noise radar technology and its applications.

Hilda A. Cerdeira graduated as Licenciada en Fisica from the Universidad Nacional de Buenos Aires and holds a Ph.D. in physics from Brown University. She was Professor at the University of Campinas, Brazil, before moving to Italy. At present she is a Scientific Member of the Condensed Matter Group of the Abdus Salam

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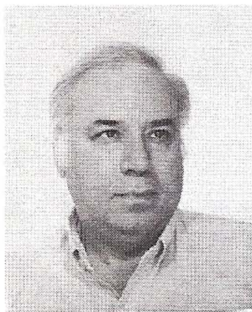

Alberto A. Colavita graduated in physics from the Universidad Nacional de Cuyo and obtained his Ph.D. at Washington University, Saint Louis, in 1974. He has taught physics for almost 20 years and is now Professor of Computer Architecture at the Universidad Nacional de San Luis and Director of the Microprocessor Laboratory of the ICTP at Trieste, Italy. He is presently developing the high-speed data acquisition system for the RICH detector of the Compass collaboration. The Compass experiment uses the SPS accelerator at CERN.

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