EPJ manuscript No.
(will be inserted by the editor)

Photoelectron multipliers based on avalanche $pn - i - pn$ structures

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Abstract. We present a new physical principle to design an optoelectronic device, which consists of a multilayered semiconductor structure, where the necessary conditions for generation of photoelectrons are met, such that it will enable sequential avalanche multiplication of electrons and holes inside two depletion slabs created around the p-n junctions of a reverse biased $pn - i - pn$ structure. The mathematical model and computer simulations of this Semiconductor Photoelectron Multiplier ($SPEM$) for different semiconductor materials are presented. Its performance is evaluated and compared with that of conventional devices. The Geiger operational mode is briefly discussed which may be used in Silicon Photomultiplier (SiPM) as an elementary photo detector to enhance its performance.

1 INTRODUCTION

The Photoelectron Multiplier or Photo Multiplier Tube (PMT) is the most efficient device to detect and amplify weak optical signals. In a PMT, photons impact an internal photocathode and transfer their energy to electrons, which then proceed to multiply themselves through a chain of electron multipliers called dynodes, ending in the anode. To construct such a device requires vacuum as the media for the photoelectrons to propagate from dynode to dynode, while rather high voltage is to be applied to the dynodes and anode to get an appreciable amplification [1,2]. Nowadays application of semiconductor photodiodes for design of an alternative device for detection of photons is a promising approach to avoid constrains and drawbacks of vacuum PMT. The simplest pin-photodiodes are quite successful to use in various physical experiments due to their reliability, compactness and low cost. Quantum efficiency of the photodiode at the maximum of spectral sensitivity reaches 90%. However, when detecting a short duration light pulses (less than $1\mu s$) one has to use an external wide-band amplifier which has rather high level of noise that does not allow detecting a flash of light with photon number less than 1000. Besides, a relatively large thickness of the depleted slab makes pin-photodiodes rather sensitive to other types of radiation (gamma rays, charged particles). More efficient might be semiconductor detectors with internal amplification similar to that in PMT. Nowadays Avalanche

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Photo Detectors (APD) are in wide use in many areas of photon detection. In APDs, optical signal is amplified due to a single, one way avalanche multiplication of the generated photoelectrons via impact ionization phenomenon.

In the 1990's a new photon detector concept was invented in the former Soviet Union, that made use of the advantages of limited Geiger mode and at the same time, allowed to retain the information on the number of primary photoelectrons over a large dynamic range [3–6]. The device designed on the basis of that concept is composed of an array of APDs working in limited Geiger mode and was called Silicon Photomultiplier (SiPM) [3–6]. This type of novel photon detector is still in its development phase. Recently this new device underwent major improvements. The development has reached a level at which many different groups now consider various possible applications of SiPM in high energy physics [7–9]. For example, Hamamatsu, one of the manufacturer of PMT, elaborated this idea to design the Multi Pixel Photon Counter [1] which is a new flat solid-state photomultiplier composed of an APD array. Nowadays SiPM is a fast-paced class of photo-detectors, which actually becomes the basis for a wide range of applications in physics applications where detection of pulsed low-intensity radiation is required. However, SiPM has some constrains, such as a limited dynamic range, long recovery time of the detection mode and rather high level of intrinsic noise.

In this paper we present a theoretical description of a new physical principle to design a semiconductor device for amplification of a weak *optical pulse* where its *multiple sequential* amplifications take place due to multiple avalanche processes happening in localized areas with high enough voltage. That is why we call this device *Semiconductor Photoelectron Multiplier* ($SPEM$) emphasizing thereby the similarity between the multiplication processes in $SPEM$ and those in PMT. The device consists of a multilayered semiconductor structure subject to conditions for the photoelectrons to produce the abovementioned sequential avalanche multiplication of electrons and holes at the two depletion slabs created around the *pn* junctions of a *pn-i-pn* structure when a reverse biased voltage is applied [10–13]. This device may be used as a primary element in SiPM which enable essential enhancement of its performance. The mathematical model and computer simulation results are presented for various regimes of $SPEM$ made of different semiconductor materials, such as Germanium, Gallium Arsenide and Silicon. Results of SPEM design and its performance evaluation are also presented along with comparison results that of conventional devices. In Section 2, we describe the device and its model suitable for main performance evaluation. In Section 3 we calculate the amplification coefficient and other parameters that characterize the $SPEM$. In Section 4 we carry out numerical simulations of the above regimes in order to justify the results obtained earlier within the frame of simplified model. Besides, we have briefly considered the Geiger operation mode in SPEM which may be achieved at the reverse bias voltage amplitude below avalanche breakdown level, which looks promising for enhancement of SiPM performance such as detector speed, intrinsic noise and shortening of SiPM recovery time. Some conclusions are given in Section 5.

2 THE DEVICE

Multiple amplification of photoelectrons due to impact ionization inside junctions occurs in reverse biased $pn - i - pn$ structure devices, which gives rise to current oscillations [10,11,13]. Applications of such structures, in particular $SPEM$, to design high energy particle detectors, were suggested in [10], while in [11] it is shown that this structure could be used to generate chaotic electromagnetic waves. In those papers the analysis of spatio-temporal dynamics of the currents inside the reverse biased $pn-$

$i-pn$ structure has been carried out with the help of its simplified model. The device studied is a multilayered semiconductor structure, consisting of two $p-n$ junctions, connected through an intrinsic, or lightly doped, semiconductor and brought close to, without exceeding, the avalanche breakdown limit via reverse bias voltage. Two depletion slabs with low conductivity arise in the neighborhood of these junctions due to the reverse bias voltage applied. The conductivity of the **i**-region is much larger than that of the depletion layer and the distribution of the electric field across this structure will have two peaks around the physical $p-n$ junctions. Therefore, in the structure described above, conditions can exist such that, in the neighborhood of the junctions there will be an **E**-field large enough to be close to the threshold for avalanche (but will not exceed it!), and at the same time the **E**-field in the **i**-region will not be large enough to cause impact ionization. This means that the impact ionization will take place **only** inside the slabs. This impact ionization produces two clouds of charges: holes and electrons ones. The electrons generated move from left to right while holes do it in the reverse direction. Since the electric field inside the **i**-region is not large enough to generate electron-hole pairs, the electrons just created will travel across and reach the second slab where, since they have been accelerated by the local **E**-field, they will cause another impact ionization event. Now, the cloud of holes will move, without changing, towards the first depletion slab 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) ones at the narrow depletion slabs after propagation through the intrinsic region.

In Refs. [10] and [11] we introduced a simplified model for this process that enables us to reduce the initial-boundary problem for partial differential equations of the drift-diffusion model to that of the much simpler mathematical object: a difference equation (DE) or difference-delay equation (DDE). The boundary conditions were obtained within the frame of a phenomenological approach using charge multiplication due to impact ionization inside the depletion slabs. For different mobilities, the primary problem is reduced to the coupled nonlinear DE or DDE. In the case of symmetric junctions the problem is reduced to two independent DE or DDE. The evolution of the initial current pulse (produced by photons) is studied for different combinations of the device parameters. It is shown in [10] that it is possible to obtain an oscillatory-like response of the considered structure after the passage of a high energy particle, when the reverse bias voltage does not exceed the avalanche break down threshold. This regime provides an internal amplification of the initial photocurrent pulse and is similar to the amplification in PMT. In order to have a complete, self consistent, description of the structure under consideration and obtain a reliable evaluation of its performance, we need to make numerical simulations of a more realistic model.

The semiconductor $pn-i-pn$ structure under consideration (Fig.1) is composed of five semiconductor layers which form two $p-n$ junctions separated by an intrinsic semiconductor. The external p_1 and n_2 layers have a higher impurity doping while the middle n_1 and p_2 regions are rather weakly doped. The profile of the doping inside the junctions corresponds to the so-called abrupt junction with a step-like description for the distribution of impurities. This approximation describes adequately the alloyed, fine diffusion and ion-implanted $p-n$ junctions [14]. Under the reverse bias voltage applied across the $pn-i-pn$ structure, where the p_1-n_1 and p_2-n_2 junctions are connected in the opposite direction, two depletion slabs with low conductivity arise in the neighborhoods of the 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 $p-n$ junctions. The photon flow, with power P_{opt}, falls onto the p_1 region of the semiconductor, while part of the radiation is reflected

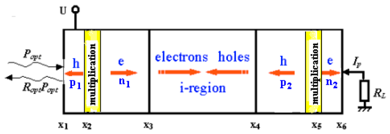


Fig. 1. Schematic of the photoelectron multiplier based on a $pn - i - pn$ structure

$R_{opt}P_{opt}$, where R_{opt} is the reflection coefficient. The absorbed photons generate electron-hole pairs inside the semiconductor, forming the initial pulse of electrons that is injected into the multiplication area of the $p_1 - n_1$ junction, where the impact ionization produces multiplication of the electrons. After that, the amplified electron current pulse flows out of the $p_1 - n_1$ junction and moves through the **i**-region towards the $p_2 - n_2$ junction. The constant **E**-field of the **i**-region forces this pulse to move with a drift velocity. Once they arrive to the multiplication layer of this junction, the charge carriers are multiplied again by impact ionization. Now, it is the turn of the pulse of holes to flow out of the $p_2 - n_2$ junction and move through the **i**-region towards the $p_1 - n_1$ junction with a constant velocity. Flying into the multiplication layer of this junction, the hole pulse induces impact ionization and, as a result, the number of charge carriers increases again. Thus, the number of pulses, and their amplitudes grow with time. This process can be stopped at any time canceling the reverse bias of the structure. Therefore, high amplification coefficients in $SPEM$ are due to sequential multiplications of the photocurrent pulse taking place inside the $p - n$ junctions because of the positive feedback described above. In this sense a $SPEM$ may be treated as a semiconductor analogue to a PMT.

3 INTERNAL AMPLIFICATION COEFFICIENT

In order to calculate the amplification coefficient, we use a model adequate to describe the process of impact ionization: a one dimensional drift-diffusion model (DDM), which describes both the static and the dynamic behavior of the charge carriers inside the semiconductor structure under the effect of both external and internal fields. At impact ionization in a $p - n$ junction, we can neglect the diffusion current being much smaller than the drift current and the dimensionless equations become [10, 11, 14]:

$$\frac{\partial E}{\partial x} = N(x) - p + n; \frac{\partial \varphi(x,t)}{\partial x} = E(x,t); \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{\partial J_n}{\partial x} + \alpha_n J_n + \alpha_p J_p - R(n,p); \tag{2}$$

$$\frac{\partial p}{\partial t} = -\frac{\partial J_p}{\partial x} + \alpha_n J_n + \alpha_p J_p - R(n,p); \tag{3}$$

$$J_n = \nu_n n, J_p = \nu_p p, J_d = \frac{\partial E}{\partial t}; \tag{4}$$

$$J = J_n + J_p + J_d; \tag{5}$$

$$R(n,p) = (np - 1)/(\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)). \tag{6}$$

Here E is the intensity of an electric field; φ is the electric potential; J, n, p, J_n, J_p, and J_d are the densities of the complete current, electrons in the conduction band, holes in the valence band, electron current, hole current and displacement current respectively; $\nu = \nu_n + \nu_p$; ν_n and ν_p are the saturation velocities of electrons and holes; $N(x) = \{-N_{a1}, -L_{p1} < x < x_2; N_{d1}, x_2 < x < L_{n1}; -N_{a2}, L_{p2} < x < x_5; N_{d2}, x_5 < x < L_{n2}\}$ is the density of impurities; N_a and N_d are the concentrations of ionized acceptors and donors respectively; $J_{st} = J_{ph} + J_{ns} + J_{ps}$ is the initial current density in the multiplication layer of the $p_1 - n_1$ junction; J_{ph} is the photocurrent generated by photons; $J_{ns}(J_{ps})$ is the saturation electron (hole) current density; α_n, α_p are the impact ionization coefficients of electrons and holes; $R(n,p)$ is the speed of recombination of electrons and holes when the Shockley-Read-Hall impact mechanism is taken into account [14]; τ_{n0} (τ_{p0}) is the electron (hole) lifetime in a $n(p)$-type semiconductor; $p_1(n_1)$ is the density of holes in the valence band (density of electrons in the conduction band), if a Fermi level coincides with an energy level of the recombination centers; L_{pi}, L_{ni} are the widths of the depleted regions of the $p_i - n_i$ junction $(i = 1, 2)$; t is the time; x is the spatial coordinate.

Under the transformations $\bar{E} = E/E_0$; $\bar{\varphi} = \varphi/\varphi_0$; $\bar{J} = J/J_0$; $\bar{n} = n/n_i$; $\bar{p} = p/n_i$; $\bar{N} = N/n_i$; $\bar{t} = t/t_0$, $\bar{x} = x/L_0$ normalsize where $E_0 = \varphi_0/L_0$ [V/m]; $L_0 = \sqrt{\epsilon\epsilon_0\varphi_0/qn_i}$ [m]; $J_0 = \frac{qn_iD_0}{L_0}$ [A/m]; $D_0 = 1$ [m/s]; $t_0 = L_0/D_0$ [s], we can find a dimensionless form of the DDM equations (1)-(6). Here n_i is the equilibrium electron concentration in the semiconductor, T is the temperature; q is the electron charge; $\epsilon\epsilon_0$ is the static dielectric constant of the semiconductor; ϵ_0 is the static dielectric constant of vacuum and k is the Boltzmann constant. Equations (1)-(6), appropriately supplied by the following initial and boundary conditions, as well as the continuity conditions for electric field and potential at the interface between p and n and i areas, become:

$$J_{pi}(L_{n1}, 0) = J_{ps}; J_{ni}(L_{p2}, 0) = J_{ns}; \tag{7}$$

$$J_p(-L_{p1}, t) = J(t) - J_{n0}(-L_{p1}, t); J_n(L_{n1}, t) = J(t) - J_{pi}(L_{n1}, t); \tag{8}$$

$$J_p(-L_{p2}, t) = J(t) - J_{n0}(L_{p2}, t); J_n(L_{n2}, t) = J(t) - J_{ps}(L_{n2}, t); \tag{9}$$

$$E(-L_{p1}, t) = 0; E(L_{n1}, t) = E_i(L_{n1}, t);\ E(L_{p2}, t) = E_i(L_{p2}, t); E(L_{n2}, t) = 0; \tag{10}$$

$$\varphi(-L_{p1}, t) = V; \varphi(L_{n1}, t) = V_i + V_2;\ \varphi(L_{p2}, t) = V_2; \varphi(L_{n2}, t) = 0; \tag{11}$$

$$E(x_{2,5} - 0, t) = E(x_{2,5} + 0, t);\ \varphi(x_{2,5} - 0, t) = \varphi(x_{2,5} + 0, t). \tag{12}$$

Here $J_{pi}(x,t)$ and $J_{ni}(x,t)$ are the electron and hole current densities in the $p_i - n_i$ junction $(i = 1, 2)$. The set of equations (1)-(6), along with the initial and boundary conditions (7 - 11) and continuity conditions (12) were solved using specific finite difference methods described in Ref. [13].

The $SPEM$ amplification coefficient is determined by [10,12]:

$$M = \prod_{j=1}^{K} M_{1j} M_{2j}; \tag{13}$$

$$M_{1j} = \left(1 - \int_{-L_{p1j}}^{L_{n1j}} \alpha_p(E_j) \exp[-\int_{-L_{p1j}}^{x} [\alpha_n(E_j) - \alpha_p(E_j)] dx']\right)^{-1}; \tag{14}$$

$$M_{2j} = \left(1 - \int_{-L_{p2j}}^{L_{n2j}} \alpha_n(E_j) \exp[-\int_{x}^{L_{p2j}} [\alpha_p(E_j) - \alpha_n(E_j)] dx']\right)^{-1}; \tag{15}$$

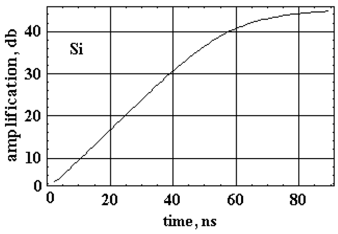
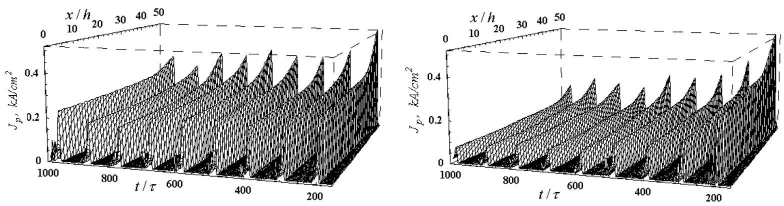


Fig. 2. Dependence of the amplification coefficient inside the $SPEM$ as a function of time

where M_{1j} (M_{2j}) is the multiplication coefficient inside the $p_1 - n_1$ ($p_2 - n_2$) junction at the $j - th$ trip of electrons and holes through the **i**-region; $j = 1, 2, 3, ..., K$; K is the number of return trips of electron and hole pulses through the **i**-region. K is given by $K = t/T$, where $T = t_{j1} + t_{j2} + t_d$; t_{j1}, t_{j2} is the drift time of electrons and holes inside the $p-n$ junctions; $t_{di} = d_i(v_{ni} + v_{pi})/v_{ni}v_{pi}$ is their transit time through the **i**-region; $v_{ni} = \mu_n E_i$ and $v_{pi} = \mu_p E_i$ are the corresponding drift velocities in the **i**-region, μ_n and μ_p their mobility and d_i is the thickness of the **i**-region. The results of computer evaluation of the $SPEM$ amplification coefficient of the avalanche Si $pn - i - pn$ structure are shown in Fig. 2. It is seen that the amplification coefficient in Si $SPEM$ exceeds 40 dB, which considerably exceeds the coefficient of internal amplification of APD [14]. In the avalanche $pn - i - pn$ structure, in the absence of an external signal, the electron-hole pairs generation may be initiated by a thermal current. This results in an instability of the equilibrium state of the structure which makes it impossible to implement a stand-by regime. Therefore some hole traps are to be implanted into the **i**-region of the $pn - i - pn$ structure to provide its stability, i.e. the stand-by regime.

Figure 3 shows the drift and recombination of holes inside the **i**-region of the $pn - i - pn$ structure having hole traps. In Fig.3, the holes drift along the negative direction of the x axis. When the lifetime equals 0.20 ns, the hole recombination current exceeds the thermal avalanche current generated in the depleted areas of the $p - n$ junctions (Fig. 3b) and the output signal decays with time. The latter ensures stability of the $SPEM$ stand-by regime.



(a) Holes lifetime: $0.21ns$ (b) Holes lifetime: $0.20ns$

Fig. 3. Drift and recombination of holes inside the **i**-region of $GaAs$ $SPEM$; $\tau = 0.15$ ns ; $h = 2.77\mu m$.

The $SPEM$ response time, τ_R, is determined as the sum of its characteristic times, namely: the drift time of carriers through the depleted areas, $t_{tr} = t_{j1} + t_{j2}$, the drift time of electrons and holes through the **i**-region, t_d and the avalanche development time, $\tau_{av} = \delta M$ where δ is the thickness of the multiplication layer. So, the speed of the $SPEM$ is determined by the time of avalanche development and the time of the carriers drift through the p-n junctions and i-region. Hence, in order to minimize the $SPEM$ response time one has to enlarge the multiplication rates in both junctions, to increase the drift velocity of charge carriers in the i-region up to the saturation velocity and to reduce the width of the i-regions. For the case $t_d >> \tau_{tr} + \tau_{av}$, the $SPEM$ response time, τ_R, is defined by

$$\tau_R = K \int_0^{d_i} (1/v_{ni}(x) + 1/v_{pi}(x))dx \tag{16}$$

More detailed consideration of the $SPEM$ response time, τ_R, will be given in the next section.

4 NOISE FACTOR AND SIGNAL-TO-NOISE RATIO

The basic source of noise in the $SPEM$ is current fluctuations caused by the multiplication. Noise produced by thermal fluctuations in the Ohm resistance of the $pn-i-pn$ structure and other $SPEM$ elements is several orders of magnitude weaker than that due to current fluctuations, thus, other contributions are negligible. The extra noise is characterized by the factor $F(M) = \langle M^2 \rangle / M^2$[14]. When only electrons are injected into the multiplication layer of the $p_2 - n_2$ junction, the noise factor is defined by the expression [14]:

$$F(M) = k_{eff} M + (2 - 1/M)(1 - k_{eff}), \tag{17}$$

where $k_{eff} = \int_0^w \alpha_p(x) M^2(x)dx / \int_0^w \alpha_n(x) M^2(x)dx$ and w is the width of the depleted region of the $p-n$ junction. After avalanche amplification the root-mean-square value of the photocurrent in the $SPEM$ can be written as $i_p = qP_{opt}M\eta/\sqrt{2}h\nu$, where q is the charge of the electron, η is the quantum efficiency and $h\nu$ is the photon energy. For the $SPEM$, the quantum efficiency is defined similarly to that of the APD [14] as the ratio of the number of photo-generated electron-hole pairs to the number of falling photons: $\eta = (I_p/q)/(P_{opt}/h\nu)$, where I_p is the photocurrent caused by absorption of optical radiation of power P_{opt} and λ is the wavelength of the photon having energy $h\nu$.

The root-mean-square value of the shot noise after amplification is equal to:

$$\langle i_s^2 \rangle = 2q(I_p + I_B + I_D)\langle M^2 \rangle B, \tag{18}$$

where I_B is the current caused by background radiation; I_D is the dark current due to thermal generation of electron-hole pairs in the depleted area and B is the $SPEM$ working frequency band. The thermal noise for an equivalent Ohm resistance R_{eq} is defined as follows [14]:

$$\langle i_T^2 \rangle = 4kT(1/R_{eq})B \tag{19}$$

The signal-to-noise ratio results from Eqs. (19)- (20) [14]:

$$S/N = \frac{i_p^2}{(\langle i_s^2 \rangle + \langle i_T^2 \rangle)} = \frac{1/2(qP_{opt}\eta/h\nu)^2}{2q(I_p + I_B + I_D)F(M)B + 4kTB/M^2 R_{eq}}. \tag{20}$$

One of the most important parameter which characterizes the quality of photoelectron multipliers is the Noise Equivalent Power (NEP). It is determined as the root-mean-square power of illuminating radiation required to achieve the *unit* signal-to-noise ratio in the photomultiplier within the 1Hz frequency band and denoted as NEP. Following this definition and using Eq.(20) we obtain [14]:

$$NEP = 2(h\nu/\eta)F(M)[1 + (1 + I_{eq}/qF(M)^2)^{1/2}], \tag{21}$$

Thus to increase the $SPEM$ sensitivity it is necessary to increase the values of M, η and R_{eq} , while those of $F(M)$, I_B and I_D are to be reduced [14]. Analysis of Equation

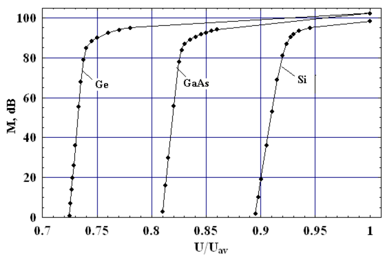


Fig. 4. Internal amplification factor for *Ge*, *Si* and *GaAs SPEM*, as a function of the voltage, taking into account the influence of spatial charge on the electric field.

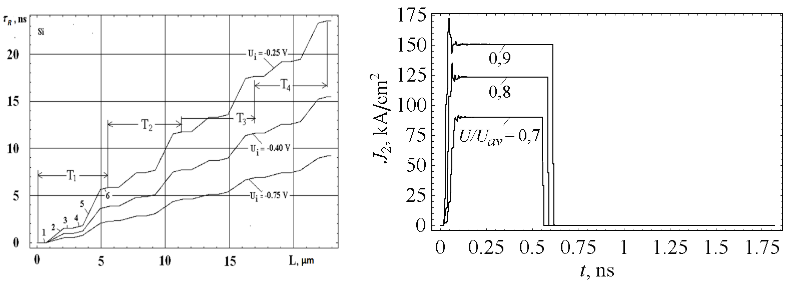
(23) has shown that without internal amplification ($M = 1$) and in the presence of background radiation, thermal noise and dark current, the unit signal-to-noise ratio can be achieved only for high enough load resistance values: $R_{eq} \geq 10^8 \Omega$ [14], while if the *SPEM* has an appreciable internal amplification ($M = 100$) this regime is reachable for the essentially smaller value of the load resistance: $R_{eq} \approx 10^4 \Omega$.

Figure 4 shows the dependence of the *SPEM* internal amplification factors for different semiconductor materials, *Ge*, *Si* and *GaAs*, as a function of the voltage. Calculations have been done according to the Eq.(1 - 11) taking into account the influence of the space charge of the generated electrons and holes by the electric field inside the *pn* -junction. It is seen in Figure 4 that the *SPEM* amplification factor saturate with voltage increase which is caused by an increase of the compensation rate of the electric field with increase in the space charge density of the generated electrons and holes. Therefore an avalanche current in the regime of avalanche breakdown (Geiger operational mode) has a limited value even without an additional resistor in the circuit. We can also see that the dynamic range of linear amplification (proportional mode) of *SPEM* from *Ge*, *Si* and *GaAs* reaches 80 dB and lies in a narrow interval of biased voltage U/U_{av} . The position of this interval on the abscissa is determined by the properties of the material since they have different dependencies of impact ionization rates on the electric field [14]. For comparison we recall that the amplification factor of APD equals $m = M^{1/K} = 80^{1/8} \approx 1.7$ dB, provided the same value of the reverse biased voltage is applied accross the $p-n$ junctions in both devices: APD and *SPEM*.

As it was discussed above the *SPEM* response time, τ_R, is determined mainly by time-of-flight of electrons and holes through the drift regions (Eq. 15) and the number, K, of electrons and holes multiplications in the depletion slabs. The latter depends on the bias voltage duration and the time to reach the Geiger operational mode. When the carrier velocities in the **i**-area of the structure are constant, the *SPEM* response time may be estimated from a simple equation: $\tau_R = KT$, where the eigen period of the structure T is to be readily calculated from Eq. (15).

Figure 5 shows the *SPEM* time response τ_R in proportional mode as function of current time expressed in terms of overall path L acquired by electrons and holes when propagating across the **i**-area and output current in Geiger operational mode.

We can see in Fig. 5a, that the *SPEM* response time is determined by the structure eigen period T and the number of multiplications K. It follows from the above considerations, that for so called proportional mode of detection, the duration of the optical pulse τ_{imp} must be shorter than half of *SPEM* eigen period $\tau_{imp} < T/2$, while the interval between them should significantly exceed the *SPEM* response time. The drawback of the suggested *SPEM* operating in proportional mode is related to the expected increase in its response time since to achieve the desirable amplification one has to use several passes across the device. Therefore, the number of multiplications



(a) (b)

Fig. 5. Proportional (a) and Geiger (b) operational modes in $SPEM$ ($Si\ pn-i-pn$ structure): (a) $SPEM$ response time τ_R as a function of the overall distance L drifted by the carriers before current saturation; (b) Current density flowing through $Si\ pn-i-pn$ structure as a function of time.

K must be minimized to optimize the $SPEM$ response time. In the above calculations we tested the operation of Si based $SPEM$ for amplification of the sequence of impulses with duration $\tau_{imp} < 1-2.5$ ns and repetition frequency $f_{imp} < 31-100$ MHz. From Fig. 5b we may notice that the increase in the electric field in the **i**-area of the $SPEM$ $E_i = U_i/d_i$ diminishes the response time from 31.8 ns ($U_i = 0.25$ V) to 9 ns ($U_i = 0.75$ V). A more significant reduction in the response time (detector speed) may be achieved if the width of the **i**-area can be reduced. Figure 5b shows $SPEM$ response for the shorter width of the **i**-area: $d_i = 6.1\mu m$). It is seen that the proportional mode of detection may have $10ps$ rise time before achieving Geiger operational mode when a constant current flows through the device independently on incoming photons. We may consider application of the suggested device as an elementary cell in SiPM array [2,4–6] for Geiger operational mode. In this mode a single photon should cause an avalanche breakdown in a cell of SiPM, while intensity, or number of photons, is estimated as the number of cells triggered to Geiger mode. In conventional SiPM this mode is achieved when applying voltage by 20%-30% above the avalanche breakdown voltage. Normally this causes an increase in the level of intrinsic noise. Besides, the recovery time strongly depends on the time of charge disappearing in pn-junctions. Since in the suggested $SPEM$ the Geiger mode may be achieved at the levels of voltage well *below* the avalanche breakdown level (see Fig. 5) we may expect faster operation of the detector and lower level of the noise inside the $SPEM$. Besides, there is much lower probability of formation of micro-plasmas, when use a lower operating voltage which is the case for $SPEM$ under consideration. It is also seen from Fig. 5 that after switching off the voltage ($t = 0.55ns$ for $U/U_av = 0.7$; $t = 0.58ns$ for $U/U_av = 0.8$; $t = 0.6ns$ for $U/U_av = 0.9$) the current through the structure disappears extremely fast because of no generation of electron-hole pairs and preserving high enough drift velocity of the carriers. So we may conclude that the $SPEM$ suggested may be used in SiPM to enhance its performance.

5 CONCLUSIONS

We have suggested and studied theoretically a new semiconductor device for detection and amplification of optical pulse signals. We have called it Semiconductor PhotoElectron Multiplier ($SPEM$) since it uses sequential photoelectron multiplication as in standard PEM. The $SPEM$ operating in proportional mode may be used for amplification of photocurrent pulse series, when optical pulse duration does not exceed the half of eigen time of the structure, while pulse repetition period should well exceed the $SPEM$ response time. We have shown that the dynamic range of the $SPEM$ amplification may reach 80 dB. Its response time is a few tens of *nanoseconds* or *picoseconds* which is determined by the width of the i-area of the $pn-i-pn$ structure, the carriers drift velocities in the **i**-area and the number of multiplication events. The $SPEM$ is a low-noise device since its Noise Equivalent Power is less than that of an Avalanche Photodetector by a factor of 10. All these characteristics make the $SPEM$ particularly attractive, mainly when one needs to operate at low working voltage, which, in particular, decreases drastically the probability of micro-plasmas generation inside the structure. The Geiger operational mode may be readily achieved in $SPEM$ even for the voltage levels below the avalanche breakdown level. The $SPEM$ has rather short switch on and switch off times and low noise level compared with those of avalanche diode detectors. The Semiconductor PhotoElectron Multiplier based upon avalanche $pn-i-pn$ structure suggested may be considered as the basis to design a realistic device for many optoelectronic applications, in particular it may be used for the design of an advanced SiPM.

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