Self-oscillations in reverse biased *pn* junction with current injection

Konstantin A. Lukin[a)]
Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine, 12 Academica Proskura St., 61085 Kharkov, Ukraine

Hilda A. Cerdeira[b)]
Abdus Salam International Center for Theoretical Physics, P.O. Box 586, 34100 Trieste, Italy

Pavel P. Maksymov
Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine, 12 Academica Proskura St., 61085 Kharkov, Ukraine

(Received 9 June 2003; accepted 23 September 2003)

The dynamics of charge carriers and the electric field in reverse biased *pn* junction in the presence of injected current is studied within the frame of a drift-diffusion model of semiconductors accounting for impact ionization. It is shown that for asymmetrical *pn* junctions and strong enough injected current, the charges of electrons and holes generated due to impact ionization make noticeable distortions in the electric field and dimensions of the depleted area which leads to time modulation of the currents flowing through the junction and voltage dropping across it. Self-oscillatory regime occurs when the reverse voltage approaches the critical value of the avalanche breakdown. This effect may be used for generation of electromagnetic oscillations in millimeter and submillimeter wave bands.
[DOI: 10.1063/1.1627939]

In Refs. 1 and 2 we have considered the spatio-temporal dynamics of currents in reverse biased *pnipn* structure due to impact ionization inside two depleted slabs when the voltage applied is close to the avalanche breakdown threshold, but does not exceed it. It has been shown that under certain conditions a single pulse generated inside such a structure may be repeatedly amplified inside the depleted slabs due to impact ionization process and multiple bouncing from the slabs.[1] This regime may be considered as the basis for design of a solid state analog to photoelectron multiplier tube, but capable of amplifying pulsed wave forms only. It may be used for detection of rare events in high energy physics. In Ref. 2 it has been shown that chaotic current self-oscillations in such a structure may be observed if one provides a nonlinear reflection of electron and/or hole currents from the depleted slabs, and how to provide it: the densities of electron and/or hole currents have to be so high that it should be capable of changing the electric field distribution inside the depleted regions. In turn, this will cause reduction of the impact ionization rate that will lead to a decrease in the number of electron-hole pairs generation. Therefore, for a larger incoming current the outgoing current will be smaller, i.e., the nonlinear reflection of currents will be provided. Studying the nonlinear reflection of currents in such structures we found that instead of a steady-state current reflection, current self-oscillations occur under certain conditions. In this letter we present the results of computer simulations (within the frame of drift-diffusion approximation) of the earlier phenomenon in a reverse biased *pn* junction under conditions of: (1) dc current injection into the junction from the outer circuit and (2) impact ionization of atoms by electrons and holes. These results enabled us to reveal the physical nature of the phenomenon and evaluate self-oscillations frequency for GaAs *pn* junction with realistic parameters.

The basic equations of the drift-diffusion model describe both the static and the dynamic behavior of the charge carriers inside the semiconductor structure under the effect of both external and intrinsic fields. For a one-dimensional model of a semiconductor structure with uniformly doped *pn* junction as shown in Fig. 1, those equations take the form[3]

$$\frac{\partial E(x,t)}{\partial x} = -\frac{q}{\epsilon\epsilon_0}[N(x)+p(x,t)-n(x,t)],$$

$$\frac{\partial \varphi(x,t)}{\partial x} = E(x,t), \tag{1}$$

$$\frac{\partial n(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + \alpha_n(E)J_n(x,t) + \alpha_p(E)J_p(x,t), \tag{2}$$

$$\frac{\partial p(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + \alpha_n(E)J_n(x,t) + \alpha_p(E)J_p(x,t), \tag{3}$$

$$J_n(x,t) = qn(x,t)v_n, \quad J_p = qp(x,t)v_p,$$

$$J_{\mathrm{dis}} = \epsilon\epsilon_0\frac{\partial E(x,t)}{\partial t}, \tag{4}$$

$$J(t) = J_n(x,t) + J_p(x,t) + J_{\mathrm{dis}}(x,t). \tag{5}$$

Here E is the electric field, φ is the electrical potential, n is density of electrons in conduction band, p is density of holes in the valence band, $\epsilon\epsilon_0$ is the dielectric constant of the semiconductor, J_n and J_p are the electron and hole current densities, respectively, J_{dis} is the displacement current density, v_n and v_p are saturation velocities of electrons and holes, respectively,

a)Electronic mail: lukin@ire.kharkov.ua
b)Electronic mail: cerdeira@ictp.trieste.it

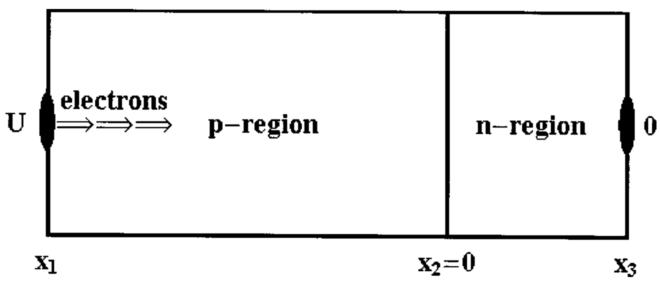

FIG. 1. Geometry of the reverse biased pn junction; $U<0$ is the bias voltage.

$$N(x)=\begin{cases}-N_a, & -w_p<x<x_2\\ N_d, & x_2<x<w_n\end{cases};$$

N_d and N_a are the concentrations of the ionized donor and acceptor atoms, respectively, q is the electron charge absolute magnitude, w_n and w_p are the sizes of the depleted regions in n and p regions, respectively, while x_2 is the coordinate of the interfaces in the abrupt pn junction under consideration, t is the time, and x is the spatial coordinate, respectively.

We have chosen the exponential approximation for impact ionization rates for electrons and holes respectively: $\alpha_{n,p}(E)=A\exp[-(b/E)^m]$, where parameters A, b, m are taken from Ref. 4. Equations (1)–(3) are to be supplied with the following boundary conditions:

$$\begin{aligned}&E(-w_p,t)=0, \quad E(w_n,t)=0,\\ &\varphi(-w_p,t)=V(t), \quad \varphi(w_n,t)=0,\\ &J_p(-w_p,t)=J(t)-J_{ns}(-w_p,t)-J_{\text{in}}(-w_p,t),\\ &J_n(w_n,t)=J(t)-J_{ps}(w_n),\end{aligned} \tag{6}$$

where $V(t)$ is the voltage drop across the pn junction; J_{ns} and J_{ps} are the electrons and holes saturation currents, and $J_{\text{in}}(-w_p,t)$ is the current injected into the pn junction.

Furthermore, according to Ref. 5, the continuity boundary conditions for the potential and electric field are to be met at the abrupt interface boundary $x=x_2\pm 0$:

$$\begin{aligned}&\varphi(x,t)_{|x=x_2-0}=\varphi(x,t)_{|x=x_2+0},\\ &\left.\frac{\partial\varphi(x,t)}{\partial x}\right|_{x=x_2-0}=\left.\frac{\partial\varphi(x,t)}{\partial x}\right|_{x=x_2+0}.\end{aligned} \tag{7}$$

Finally, we have to add initial conditions for all time dependent values: electron and hole current densities, electric field and potential distributions, and the dimensions of the depleted regions

$$\begin{aligned}&J_p(x,0)=-J^0_{\text{in}}(-w_p), \quad J_n(w_n,0)=0,\\ &\varphi(x,0)=\varphi^{\text{Static}}(x), \quad E(x,0)=E^{\text{Static}}(x),\\ &w_{n(p)}(0)=w^{\text{Static}}_{n(p)},\end{aligned} \tag{8}$$

where $J^0_{\text{in}}(-w_p)=\text{Const}$ is the constant dc current injected into the pn junction, and the static values are obtained from Poisson's equation, for no impact ionization. Equations (1)–(5) with boundary conditions (6), (7) and initial conditions (8) have been solved numerically with help of finite difference method suggested in Ref. 5.

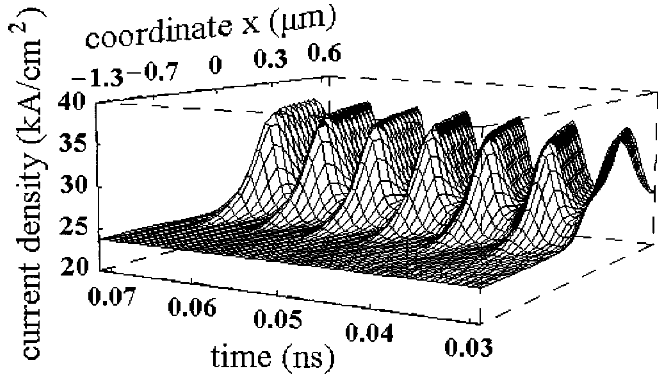

FIG. 2. Electron current density as a function of time t and coordinate x in the pn junction, when a reverse bias voltage $U=-41.5$ V ($U/U_{\text{av}}=0.998$) is applied.

Here, we investigated a GaAs pn junction with $N_a=2\times10^{16}$ cm^{-3}; $N_d=5.5\times10^{16}$ cm^{-3}, $U_{\text{av}}=-41.576$ V and $J_{\text{lim}}=88$ kA/cm^2. The value of the reverse voltage applied has been chosen to bring the pn junction close to (but not exceed!) the avalanche breakdown threshold for the given structure. In this case, the current $J^0_{\text{in}}(-w_p)=\text{Const}$ injected into the pn junction from the outer circuit at the point $x=x_1$ (see Fig. 1) will cause impact ionization of the electron-hole pairs inside the depleted slab within the vicinity of the electric field maximum. The density of these charge carriers is to be large enough to be able to change the electric field distribution within the depleted region as pointed in Ref. 1. The symmetry breaking of the pn junction geometry and doping rates makes the holes inside the p region remain for a longer time than the electrons, while the electrons do the same in the n region. This causes a reduction of the electric field amplitude, strong enough to change the impact ionization rate. The latter leads to a reduction of the number of electron-holes pairs generated by impact ionization. With the reduction of the electron and hole densities, the electric field will restore its former amplitude, and, again, the impact ionization rate will increase, causing an increase in hole and electron densities again. Therefore, we should expect an oscillatory regime for a given set of pn-junction parameters. Computer simulations have been done for the case of $U<U_{\text{av}}$. The mesh steps along time, τ, and spatial, h, axis have been chosen according to the Courant condition $\tau\leqslant hv$, where v is the saturation velocity of charge carriers.

Figure 2 shows the spatiotemporal behavior of the electrons current density for a strong injected current comparable to the pn-junction limiting current, while the reverse bias voltage applied is relatively low: $U=-41.5$ V ($U/U_{\text{av}}=0.998$). We see undamped current oscillations with rather strong amplitude and drift motion of the charge carriers towards the pn-junction depleted region boundary. In order to understand why such self-oscillatory regime takes place in this semiconductor structure, we studied the temporal behavior of all time dependent quantities, such as electric field, voltage drop across the depleted region, the dimension of the depleted region itself and total charge within the depleted region.

Figures 3(a) and 3(b) show the spatial distributions of the electron and hole densities at three points in time, while in Fig. 3(c) we do the same for the electric field across the

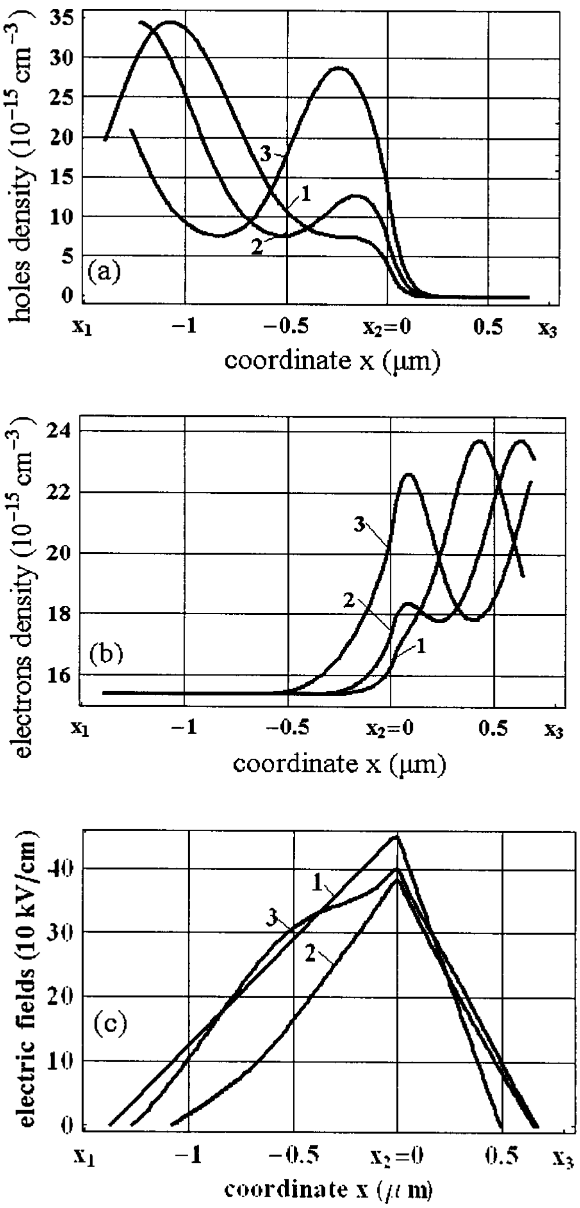

FIG. 3. Spatial distributions of the charge densities across the *pn* junction for $U=-41.5$ V ($U/U_{av}=0.998$): (a) the hole density, (b) the electron density, and (c) the electric field distribution $E(x,t)$ across the *pn* junction. The labels 1, 2, and 3 correspond to different values of oscillating electric field which corresponds to its maximum, medium and minimum values, respectively. Coordinates (x_1, x_2, x_3) determine the *pn* region as shown in Fig. 1.

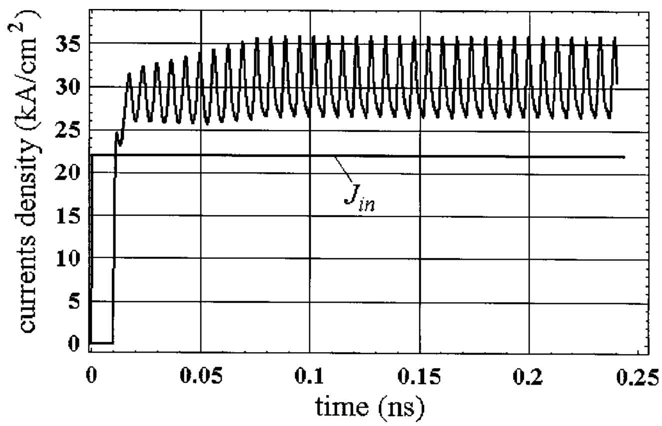

FIG. 4. Time dependence of the electron current density $J_n(w_n, t)$ approaching a steady state oscillatory regime in *pn* junction having avalanche breakdown voltage $U_{av}=-41.575$ V and limiting current $J_{lim}=88$ kA/cm^2 for injection current $J_{in}(-w_p, t)=0.25 J_{lim}$ and bias voltage $U=-39.8$ V ($U/U_{av}=0.96$).

pn junction for the oscillatory regime. The curves labeled by numbers 1, 2, and 3 correspond to different states of the oscillating electric field which corresponds to its maximum, medium, and minimum values, respectively. We see from them that in the depleted region of the *pn* junction the density of electrons generated due to impact ionization prevails in the *n* region while the density of the generated holes prevails in the *p* region. Such charge distribution provides compensation of the electric fields created by the *pn*-junction space charge that is clearly seen in Fig. 3(c). The rate of the *E*-field compensation depends on the number of electron-hole pairs generated and their space-time distribution within the depleted region, which, in turn, depends on the doping and impact ionization rates, applied voltage, saturation velocities, etc. It is important that the *pn* junction should have an asymmetry in both geometry and doping rates in order to avoid mutual compensation of space charge fields of electrons and holes generated via impact ionization. The transients of the self-oscillatory regime after constant dc current injection into *p* region are shown in Fig. 4. We can see how the current self-oscillations get started and evolve to a steady state oscillatory regime with a certain amplitude and frequency. We also evaluated the dependence of the oscillation frequency on the doping rate. We found that the frequency of the current self-oscillations becomes higher with increasing of the doping rates (decreasing of avalanche breakdown voltage U_{av}). Change the avalanche breakdown voltage from -100 to -20 V causes an increase in the self-oscillation frequency from 50 up to 400 GHz. These results confirm the existence of current self-oscillations (see also Ref. 1) in the reverse biased *pn* junction with a strong current injection and provide a nice illustration to explain a physical mechanism that causes them.

In conclusion, we have shown that in the reverse biased asymmetrical *pn* junction, being not equally doped, it is possible to provide a nonlinear transformation of incoming current into outgoing one due to mutual dependence of the electric field and impact ionization rate. The latter is caused by dynamical compensation of the static field in the *pn* junction by the charge of electrons and holes generated by impact ionization. For the voltage close to the avalanche breakdown threshold and injection current comparable with the limiting current of the *pn* junction the current self-oscillatory regime occurs.

This effect may be used for the design of semiconductor oscillators to generate electromagnetic signals in millimeter and submillimeter wave bands.

[1] K. A. Lukin, Hilda A. Cerdeira, and A. A. Colavita, IEEE Trans. Electron Devices **43**, 473 (1996).
[2] K. A. Lukin, H. A. Cerdeira, and A. A. Colavita, Appl. Phys. Lett. **71**, 2484 (1997).
[3] K. A. Lukin, H. A. Cerdeira, A. A. Colavita, and P. P. Maksymov, Int. J. Model. Simulat. **23**, 77 (2003).
[4] S. M. Sze, *Physics of Semiconductor Device* (Wiley, New York, 1981).
[5] K. A. Lukin and P. P. Maksymov, Radiophysics and Electronics **4**, 87 (1999).