MICROWAVE CHARACTERISTICS OF BARITT DIODES WITH NON - UNIFORM DISTRIBUTION OF TRAPS CONCENTRATION IN TRANSIT-TIME REGION

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Abstract

Impedance characteristics of the BARITT microwave structures with traps level exponentially distributed in the forbidden gap of the drift (transit - time) region of a semiconductor are examined. It is shown that in results the non-uniform distribution of the traps leads to larger dynamic negative resistance in absolute value in comparison with the case of the uniform distributions of traps.

1. INTRODUCTION

Barrier-injection transit-time (BARITT) devices are being utilized in microwave systems as oscillators, low-power amplifiers, mixers, detectors [1-6], heterodyne photodetectors [7], and in Doppler radar systems [8]. At present, the BARITT diodes (BARITTs) operated at lower power and lower efficiency in comparison, for example, with IMPATTs, but had better noise characteristics. Therefore it is expected that microwave parameters of BARITTs should be improved. On the other hand, it is known that the basic static and microwave characteristics of such injection - transit - time diodes depend largely on a condition and concentration of surface effects in the injecting contact, the structure of distributions of the doping impurity, defects, capture centers etc. [9-12]. The presence in the forbidden gap a various type of traps for mobile charge carriers is integral attribute of real semiconductors. The impurity levels presence in the transit region depending on their energy distribution and other characteristics of centers, no doubt, should affect on the static and dynamic characteristics of BARITTs. The influence of uniformly distributed in the transit region impurities creating in the forbidden gap of the semiconductor trap levels (traps), on the BARITTs characteristics is considered by us earlier (see, for example, [9]). In the present work a case of the influence of the non-uniform (exponential) distribution on the transit - time length of the impurities creating the traps for injected minority charge carriers, on the microwave characteristics of BARITTs is analyzed.

2. THEORY

We shall consider a silicon $p+$ - n - $p+$ structure. We assume that in the n-layer uniformly doped by shallow donors with the concentration N_g the impurities creating non-uniformly (exponentially) distributed traps for injected holes (Fig. 1) are available. The influence of such traps on the BARITTs characteristics can strongly have an effect at low levels of injection when the traps are partially filled and, in a smaller degree, at large levels of injection, when the traps are completely filled. In such a semiconductor structure parts of the injected carriers are captured by the traps creating a motionless space charge which can essentially change the form of the current-voltage characteristics and the impedance of the injection-transit-time diode. In the present treatment it is assumed that the voltage applied to the structure is greater than the voltage which is necessary to realize the punch-through condition and that the electric field intensity is not high enough for the field to empty the traps. With such field the relation between free and captured carriers changes because of the injection of free carriers. In normal mode of operations of the $p+$ - n - $p+$ BARITTs injected holes, in a vicinity of a maximum of a potential barrier, are diffused in the beginning through a region of a zero or very low electrical field with low value of the drift velocity. On an initial region of movement (after the injector) holes repeated (dependent on the relation of the time of flight to the period of a signal) the interaction with the traps, it will be more effective to influence on a delay of an alternating current from the voltage. That will increase the dynamic negative resistance in absolute value. In the other part of the transit region, where the electrical field intensity quickly grows and holes are moved with higher velocities, the traps influence will be less effective. Therefore, the large concentration of the traps in the initial region a transit space should strongly "brake" of holes. Such "delay" of holes hereinafter at their movement in the transit region, because of their capture on subsequent traps and additional "delay", promotes more significant delay of an alternating current from the field and improvement of the microwave characteristics of BARITTs.

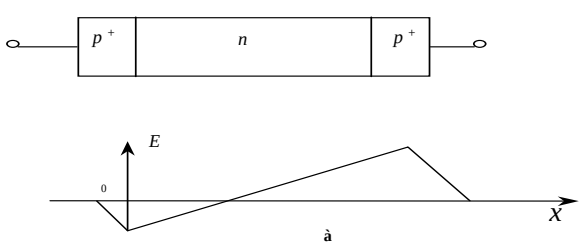

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Figure 1. Schematic diagram of $p^+ - n - p^+$ BARITT structure. a- electric distribution, b- potential profile reach- through.

Let concentration profile of the traps submits to the regularity:

$$N_t = N_{t0} \exp(-\alpha x), \tag{1}$$

where N_{t0} is the concentration of the traps on an initial part of the transit region, α is the factor determining a gradient of the impurities created the traps.

For the small-signal analysis, usually the parameters are set the sum of constant and small variable components, for example

$$\begin{aligned} I(t) &= I_0 + I_1 \exp(j\omega t), \\ E(x,t) &= E_0 + E_1 \exp(j\omega t), \\ p(x,t) &= p_0 + p_1(j\omega t), \\ N_+ &= N_{+0} + N_{+1}(j\omega t) \end{aligned} \tag{2}$$

We shall confine ourselves to the case of constant mobility μ. If the electron component of current and the diffusion component of the hole current are neglected, then the total current in the $n-$layer is the sum of the drift component of hole current and the displacement current

$$I = \rho v + \varepsilon_1 \frac{\partial E}{\partial t}, \tag{3}$$

where ρ is the concentration of mobile carriers and v their velocity.

The injected holes together with the fixed charge in the $n-$region determine the value of E according to the Poisson equation

$$\varepsilon_1 \frac{\partial E}{\partial x} = \rho + q\left(N_D + N_+\right) \tag{4}$$

where N_D is the concentration of shallow donors in the $n-$layer. In equilibrium the donor impurities lying near the bottom of the conduction band are ionized and the exchange of holes is accomplished only between the valence band and trap levels. Then the concentration of holes captured at the trapping levels is

$$N_+ = \frac{pN_t}{p + p_t + \left(j\omega N_{+1}/\alpha N_+\right)} \tag{5}$$

where α is the capture coefficient of the holes at the trap level, p is the concentration of holes and p_t is the Shockley-Read state factor (the concentration of holes in the valence band, when the imref coincides with the trap level). If p_1 is considerably less than p_0 and p_t then for the case of large values of the capture coefficient α

$$N_+ \cong \frac{p_0 N_t}{p_0 + p_t}, \qquad N_{+1} = \frac{p_1 N_t}{p_0 + p_t}. \tag{6}$$

This approximation corresponds to the most real situation when α is a large quantity.

From Eqns. (3) and (4) we have constant components

$$I_0 = \rho_0 v_0, \tag{7}$$

$$\varepsilon_1 \frac{\partial E_0}{\partial x} = \rho_0 + q\left(N_D + N_{+0}\right) \tag{8}$$

and for alternating components

$$I_1(t) = \rho_0 v_1 + \rho_1 v_0 + j\omega\varepsilon_1 E_1, \tag{9}$$

$$\varepsilon_1 \frac{\partial E_1}{\partial x} = \rho_1 + eN_{+1}. \tag{10}$$

Integrating the Eqns. (9) and (10) we obtain the small-signal characteristics of the device. To realize the integration it is necessary to specify the boundary conditions. Near the potential barrier at the source both current components (drift and diffusion) are important. Therefore we shall take the plane where the potential energy passes through its maximum as the effective (virtual) source for injection of carriers [12-15]. The holes are injected through this plane with initial velocities, the source therefore has a finite

conductivity making it possible to control the rate of injection, the injection phase delay of the current and the presence of the essential DNR. In the case of current limited by a space charge it is usually accepted that the source has an infinite conductivity, and for the current limited by emission the source is characterized by zero conductivity. In the system being studied the velocity of the carriers caused by changing the electric field $\Delta v = \mu \Delta E$ takes place during a few lattice collisions and even at microwave frequencies it can be accepted as instantaneous. By changing the field a rearrangement of the space-charge takes place and a new equilibrium is obtained. Then the alternating small-signal field at the source plane modulates only the velocity of carriers and not the concentration of the charge carriers. Then the current of particles I_{1p} is in-phase with the local field E_{1S} i.e.

$$I_{1p} = \sigma E_{1S} . \tag{11}$$

The average particle current in the plane of the barrier maximum is equal to

$$I_0 = \rho_{0S} v_{0S} \tag{12}$$

where p_{0S} and v_{0S} are the average charge and the charge velocity in this plane so the effective small-signal conductivity of the source equals [9,13]

$$\sigma = \frac{\mu_p I_0}{v_{0S}} . \tag{13}$$

The total small-signal current is the sum of the particle current and displacement current at the virtual source

$$I_1 = I_{1p} + j\omega\varepsilon_1 E_{1S} . \tag{14}$$

Hence

$$E_{1S} = \frac{I_1}{\sigma + j\omega\varepsilon_1} . \tag{15}$$

The technique of calculation [10-12] was used below, and for v_{0S} the results of [13] were used.

The small-signal injection approximations are considered

$$p_0 + p_1 \exp(j\omega t) < p_t , \qquad N_{+0} \cong \frac{p_0 N_t}{p_t} , \qquad N_{+1} \cong \frac{p_1 N_t}{p_t} . \tag{16}$$

From Eqns. (1), (3), (4) and (5) in a examined case it is easy matter to obtain the following for the equation of flight:

$$\frac{d^2x}{dt^2} - \omega_1 \frac{dx}{dt} = \frac{I_0 \mu_p}{\varepsilon_1}\left(1 + \frac{N_{t0}}{P_t} e^{-\alpha x}\right), \tag{17}$$

where $\omega_1 = \frac{q\mu_p N_g}{\varepsilon_1}$, $\frac{dx}{dt} = V_0$, x is the current coordinate, t is the time, v_0 is the velocity of holes in the transit space, $\varepsilon_1 = \varepsilon\varepsilon_0$ is the dielectric constant of the semiconductor.

The solution of the equation (17) under boundary conditions x=0, t=0,, $\frac{dx}{dt} = V_{OS}$, where V_{OS} is the velocity of holes on the injecting solution plane, gives:

$$x(t) = \frac{\alpha}{\omega_1 k}\left(e^{kt} - kt - 1\right) + \frac{V_{os}}{k}\left(e^{kt} - 1\right), \tag{18}$$

where $a = \frac{\mu_p I_0 \beta}{\varepsilon_1 \omega_1}$, $\beta = 1 + \frac{N_{t0}}{p_t}$, $k = \frac{\omega_1 + \sqrt{\omega^2{}_1 - 4\alpha b}}{2}$, $b = \frac{I_0 \mu_p}{\varepsilon_1} \frac{N_{t0}}{p_t}$.

By the use of the equation (18) it is possible to calculate the velocity of holes and spatial - temporary diagrams of their flight for various parameters, in particular, at the various regularities of the change of the traps concentration. At N_{t0}=0 (β=1) Eq. (18) passes in well known expression for usual BARITTs [1, 13-15].

For the alternating voltage we obtain the nonlinear non-uniform equation of the second order:

$$\frac{d^2U_1}{dt^2} + \left(j\omega\beta - \omega_1\right)\frac{dU_1}{dt} = -\frac{I_1 V_o}{\varepsilon_1}\left(\beta - \alpha\gamma_0 x(t)\right) + j\omega\gamma_0 \alpha x(t)\frac{dU_1}{dt}, \tag{19}$$

where $\gamma_0 = \frac{N_{t0}}{p_t} = \beta - 1$, $\omega = 2\pi f$ is cyclic frequency of the signal, U_1 is the alternating voltage. For the solution of Eq.(19) we simplify the expression (18) by the decomposition of exponential terms in a series and restriction by three terms of the decomposition. We obtain:

$$x(t) \approx V_{os} t + \alpha_1 t^2, \ \alpha_1 = \frac{k}{2}\left(\alpha + V_{os}\right)$$

and for the equation (19) we have:

$$\frac{d^2U_1}{dt^2}+\xi\frac{dU_1}{dt}\approx-\frac{I_1V_0\beta}{\varepsilon_1}+\frac{I_1V_{0s}}{\varepsilon_1}\gamma_0\alpha\left(V_{os}t+\alpha_1t^2\right)+\xi_1\left(V_{os}t+\alpha_1t^2\right)\frac{dU_1}{dt}, \quad (20)$$

where $\xi = j\omega\beta-\omega_1$, $\xi_1 = j\gamma_0\omega\alpha$.

The solution of the equation (20) where the right part is a sum of two functions is possible to present as the sum $U_1=U_{11}+U_{12}$, where according to the solution of the equations U_{11} and U_{12} are:

$$\frac{d^2U_{11}}{dt^2}+\xi\frac{dU_{11}}{dt}\approx-\frac{I_1V_0\beta}{\varepsilon_1}, \quad (21)$$

$$\frac{d^2U_{12}}{dt^2}+\xi\frac{dU_{12}}{dt}\approx\frac{I_1V_{0s}}{\varepsilon_1}\gamma_0\left(V_{os}t+\alpha_1t^2\right)+\xi_1\left(V_{os}t+\alpha_1t^2\right)\frac{dU_{12}}{dt}, \quad (22)$$

The equation (21) coincides with the equation for BARITTs for the case of the traps uniformly distributed on the coordinate and is considered by us in Refs. [9-12]. The equation (22) is solved only at further linearization - at a simplification of the expression x(t) up to $x(t)=V_{os}\,t$, as at all values $N_{t0}>0$, the following inequality is always obeyed:

$$t_{max}=T<<2\left[k\left(1+\frac{a}{V_{os}}\right)\right]^{-1},$$

where T is the time of flight of holes through the n-layer.

Physically such linearization is much justified by that, as was marked in the beginning, the velocity of holes on an initial region of the space is low, and the intensity of the electrical field in a vicinity of the plane of injection is also small. The component U_{12} characterizes just that part of the voltage U_1 which is introduced by the "non-uniform" distribution of the traps in the initial part of the transit - time region. The component U_{11} characterizes the other part of the transit region and includes values for the uniform distribution of the traps [9-12] and at complete its absence [13-15]. The solution of the equation (21) and the results of the analysis are discussed by us earlier in Refs.[9, 10] and are not presented here. There is of interest the component of an impedance caused by the non-uniform distribution of the traps, that can be obtained from the solution of the equation (22). It looks like:

$$U_{12} = -\frac{b_1}{\xi}\left\{T\left(\frac{2}{\xi} - T\right) + \left(e^{-\xi T} - 1\right)\left(\frac{2}{\xi^2} - \frac{b_0}{b_t}\right)\right\} - \frac{b_0}{\xi_1 V_{os}}\left(e^{\xi V_{os} T} - 1\right), \tag{23}$$

where $b_1 = \frac{I_1 V_{0S}{}^2 \alpha\gamma_0}{2\varepsilon_1}$, $b_0 = \frac{I_1 V_{0S}}{\sigma + j\omega\varepsilon_1}$, I_1 is full alternating current, σ is the small - signal conductivity of a contact. We shall note, that at α = 0, U_{12}=0, the expressions (18) and (19) coincide with the appropriate expressions obtained for the case of the uniform distribution of the traps.

In the expression for the impedance of a diode with the cross-section S at the frequency ω,: active component R_{12} caused U_{12} is equal:

$$R_{12} = \left\{2b_3\left(\theta_1^2 - \theta_0^2\right)\left[1 + b_3\left(\theta_1 b_6 - \theta_0 b_7\right)\right] + \theta_1 - b_4\left[b_6\left(\theta_1 + \theta_0\theta_S\right) - b_7\left(\theta_0 + \theta_1\theta_S\right)\right] - 4b_3^2\theta_1\theta_0\left(\theta_1 b_7 + \theta_0 b_6\right)\right\}$$
$$- b_5\left(b_8\theta_S - sin\left(\theta\beta_1\right)\right), \tag{24}$$

where

$$b_2 = \frac{V_{0S}\alpha\gamma_0 T^3}{2\varepsilon_1\left(\theta_0^2 + \theta_1^2\right)}, \quad b_3 = \frac{1}{\theta_1^2 + \theta_2^2}, \quad b_4 = \frac{2\varepsilon_1}{\mu_p I_0 T^2 \alpha\gamma_0\left(1 + \theta_S^2\right)},$$

$$b_5 = \frac{V_{OS}^2 T}{\mu_p I_0 \gamma_0 \alpha\theta\left(1 + \theta_S^2\right)}, \quad b_6 = 1 - e^{\theta_1}\cdot cos\,\theta_0, \quad b_7 = e^{\theta_1}\cdot sin\,\theta_0, \quad b_8 = cos\left(\theta\beta_1\right) - 1,$$

$$\beta_1 = V_{0S}\gamma_0\alpha T, \quad \theta_S = \frac{\omega\varepsilon_1}{\sigma}, \quad \sigma = \frac{\mu_p I_0}{V_{0S}}, \quad \theta = \omega T, \quad \theta_1 = \omega_1 T, \quad \theta_0 = \theta\beta.$$

The analysis of the expression (24) shown that the component of the impedance R_{12} (in addition to the active component of the impedance with the uniformly distributed traps, considered in Ref. [9, 10]) can accept a negative value at certain angles of the flight θ (the frequencies of the signal).

These estimations prove to be true by results of numerical calculation carried out on the PC at the following values of parameters, included in expression (24): $\mu \cong 450$ ñm^2/V s; $N_g \approx 10^{15}$ ñm^{-3}, I_0=50 A/ñm^2; $\alpha \approx 6{,}8$; $\gamma_0 \approx 0{,}5$; $V_{os} \approx 10^5$ ñm/s; $\theta_0 \approx 2$; S=1,25 .10^{-4} ñm^2, $\theta_S \approx 0{,}16\theta$. For example, at $\beta\theta = 1{,}5\pi$, being the optimum angle of flight for BARITT, R_{12} for the above-stated values of parameters and β=2 is equal - 0.4 Ohm and with the increase $\gamma_0(\beta)$ and reduction of the frequency θ tends to an increase in absolute value, but the

frequency band, where the dynamic negative resistance takes place, is narrowed and displaced toward a lower frequency range (Fig.2.). The general value of the active negative resistance is equal $R=R_{11} + R_{12}$, where R_{11} is the active negative resistance caused by the uniform distribution of the traps and considered in Refs. [9,10]. It tends to an increase in the absolute value at low level of injection with an increase of the concentration of the traps. R_{12} is the negative resistance caused by the non-uniform distribution of the traps. As it is shown in Refs.[9-11], the existence of empty traps results in a delay in degenerative feed back due to a capture of injected holes by the traps during their drift and ensuing re-emission of holes into the valence band. This delay of charge carriers with respect to the field provides an increase in the magnitude of the active negative resistance R with simultaneous decrease in possible range of transit angles.

Thus, the non-uniform distribution of the traps makes the additional contribution during the formation of the dynamic negative resistance in BARITT and can result in more substantial growth of the latter on absolute value.

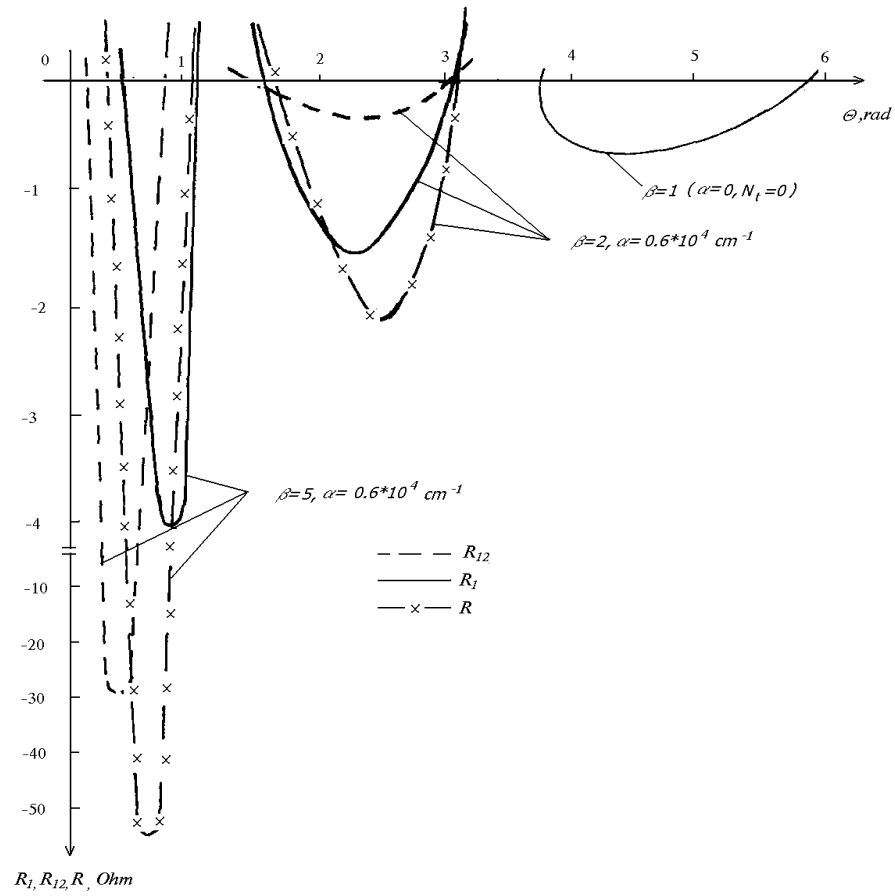

Figure 2. Active negative resistance R_1 , R_{12} , $R=R_1+R_{12}$ as a function of the transit angle θ for values of the parameter β. Device area is equal 10^{-4} cm^2, the drift space is equal 5μm, the doping density is equal $1.25*10^{15}$ cm^{-3}, that is equivalent to 4 Ohm*cm for the n - type silicon, the hole mobility μ is equal 450 cm^2/Vs, bias current I_0=10A/cm^2, average charge velocity in the injection plane $V_{os}=9*10^5$ cm/s [13].

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