Analysis of a DAR IMPATT Diode for High Frequency Part of Millimetric Region

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Abstract: - The analysis and optimization of the $n^+pvnp^+$ avalanche diode structure that includes two avalanche regions have been realized on basis of the nonlinear model and special optimization procedure. The admittance characteristics of the DAR diode were analyzed in very wide frequency band from 30 up to 360 GHz and had been optimized for the third frequency band near the 300 GHz.

Key Words: - Implicit numerical scheme, active layer structure analysis, DAR IMPATT diode.

1 Introduction

The power generation in short part of millimeter region is one of the important problems of modern microwave electronics. The IMPATT diodes of different structures are used very frequently in microwave systems. The single drift region (SDR) and the double drift region (DDR) IMPATT diodes are very well known and used successfully for the microwave power generation in millimeter region [1-2]. From the famous paper of Read [3] the main idea to obtain the negative resistance was defined on the basis of the phase difference being produced between RF voltage and RF current due to delay in the avalanche build-up process and the transit time of charge carriers. However an IMPATT diode that has double avalanche regions (DAR) can produce an avalanche delay, which alone can satisfy conditions necessary to generate microwave power [4-7]. This diode can be defined for instance by means of the structure $n^+pvnp^+$ in Fig. 1.

The characteristics of this diode were analyzed in [7] by means of approximate model. The authors affirm that the diode active properties are produced in many frequency bands for any drift zone width. Our preliminary analysis that was obtained on basis of the sufficiently precise model [8-9] contradicts to the results [7]. We obtained three active frequency regions for proposed diode. We have been optimized the DAR IMPATT diode for second frequency region in [9]. The present paper is focused to the analysis of DAR diode for the third frequency region near 300 GHz.

2 Nonlinear Model

The drift-diffusion model, which is used for the diode analysis, consists of two continuity equations for the electrons and holes, the Poisson equation for the potential distribution in semiconductor structure and necessary boundary conditions as for continuity equations and for the Poisson equation. The principal equations can be presented in next form:

$$\begin{align*}
\frac{\partial n(x,t)}{\partial t} & = \frac{\partial J_n(x,t)}{\partial x} + \alpha_n J_n(x,t) + \alpha_p J_p(x,t) \\
\frac{\partial p(x,t)}{\partial t} & = -\frac{\partial J_p(x,t)}{\partial x} + \alpha_n J_n(x,t) + \alpha_p J_p(x,t)
\end{align*}$$

(1)

Figure 1. Doping profile for DAR IMPATT diode.
where
\[
J_n(x,t) = n(x,t) \frac{\partial n(x,t)}{\partial x} + D_n, \quad J_p(x,t) = p(x,t) \frac{\partial p(x,t)}{\partial x} + D_p
\]

\(n, p\) are the concentrations of electrons and holes; 
\(J_n, J_p\) are the current densities; 
\(\alpha_n, \alpha_p\) are the ionization coefficients; 
\(V_n, V_p\) are the drift velocities; 
\(D_n, D_p\) are the diffusion coefficients. The dependences of the ionization coefficients on field and temperature and charge transport properties have been approximated using the approach in [10-13].

The boundary conditions for this system include concentration and current definition for contact points and can be written as follows:
\[
\begin{align*}
n(0,t) &= N_D(0) \quad \text{at } x = 0; \\
p(l_0,t) &= N_A(l_0) \quad \text{at } x = l_0; \\
J_n(l_0,t) &= J_{ns}; \\
J_p(l_0,t) &= J_{ps},
\end{align*}
\]

\(J_{ns}, J_{ps}\) are the electron current and the hole current for inversely biased p-n junction; 
\(N_D(0), N_A(l_0)\) are the concentrations of donors and acceptors at two end space points \(x = 0\) and \(x = l_0\); where \(l_0\) is the length of the active layer of semiconductor structure.

The electrical field distribution in semiconductor structure can be obtained from the Poisson equation. As electron and hole concentrations are functions of the time, therefore, this equation is the time dependent too and time is the equation parameter. The Poisson equation for the above-defined problem has the following normalized form:
\[
\frac{\partial E(x,t)}{\partial x} = -\frac{\partial^2 U(x,t)}{\partial x^2} = N_D(x) - N_A(x) + \rho(x,t) - n(x,t)
\]

\(i = 1, 2, \ldots, I_l - 1; \quad k = 0, 1, 2, \ldots, \infty\)

where 
\(N_D(x), N_A(x)\) are the concentrations of donors and acceptors accordingly, 
\(U(x,t)\) is the potential, 
\(E(x,t)\) is the electrical field. The boundary conditions for this equation are:
\[
\begin{align*}
U(0,t) &= U_0; \\
U(l_0,t) &= \sum_{m=1}^{M} U_m \sin (\omega mt + \varphi_m)
\end{align*}
\]

\(U_0\) is the DC voltage on diode contacts; 
\(U_m\) is the amplitude of harmonic number \(m\) in diode contacts; 
\(\omega\) is the fundamental frequency; 
\(\varphi_m\) is the phase of harmonic number \(m\); 
\(M\) is the number of harmonics. In this paper we analyze one harmonic regime only \((M=1)\) and in this case the phase \(\varphi_m\) can be define as 0. Concrete values of the voltages \(U_0, U_1\) and frequency \(\omega\) have been defined during the analysis in section 5. Equations (1)-(4) adequately describe processes in the IMPATT diode in a wide frequency band. However, numerical solution of this system of equations is very difficult due to existing of a sharp dependence of equation coefficients on electric field. Explicit numerical schemes have poor stability and require a lot of computing time for good calculation accuracy obtaining [14]. It is more advantageous to use implicit numerical scheme that has a significant property of absolute stability. Computational efficiency and numerical algorithm accuracy are improved by applying the space and the time coordinates symmetric approximation.

After approximation of functions and its differentials the system (1) is transformed to the implicit modified Crank-Nicholson numerical scheme. This modification consists of two numerical systems each of them having three-diagonal matrix. These systems are defined by form:
\[
\begin{align*}
-\left( a_n - b_n \right) n^{i+1}_n + & \left( 1 + 2a_n \right) n^i_n - \left( a_n + b_n \right) n^{i-1}_n = \\
& a_n n^i_n + \left( 1 - 2a_n \right) n^i_n + a_n n^{i+1}_n + b_n \left( n^{i+1}_n - n^{i-1}_n \right) + a_n \left( \mathbf{\nabla} \cdot \mathbf{V}_n \cdot n^i_n + r \cdot D_n \cdot \left( n^{i+1}_n - n^{i-1}_n \right) \right) \\
& + a_p \left( \mathbf{\nabla} \cdot \mathbf{V}_p \cdot p^i_n - r \cdot D_p \cdot \left( p^{i+1}_n - p^{i-1}_n \right) \right) \\
- \left( a_p + b_p \right) p^{i+1}_n + & \left( 1 + 2a_p \right) p^i_p - \left( a_p - b_p \right) p^{i-1}_n = \\
& a_p p^i_p + \left( 1 - 2a_p \right) p^i_p + a_p p^{i+1}_p - b_p \left( p^{i+1}_p - p^{i-1}_p \right) + a_p \left( \mathbf{\nabla} \cdot \mathbf{V}_p \cdot p^i_p - r \cdot D_p \cdot \left( p^{i+1}_p - p^{i-1}_p \right) \right) \\
& + a_n \left( \mathbf{\nabla} \cdot \mathbf{V}_n \cdot n^i_n + r \cdot D_n \cdot \left( n^{i+1}_n - n^{i-1}_n \right) \right)
\end{align*}
\]

The approximation of the Poisson equation is performed using ordinary finite difference scheme at every time step \(k\):
\[
U_{i-1}^k - 2U_i^k + U_{i+1}^k = h^2 \left( N_{D_i} - N_{A_i} + p_i^k - n_i^k \right)
\]
Numerical algorithm for the calculation of IMPATT diode characteristics consists of the following stages: 1) the voltage is calculated at the diode contacts for every time step by formula (4); 2) the voltage distribution is calculated at every space point from the Poisson equation (6) by factorization method [15], the electrical field distribution along the diode active layer is calculated; 3) the charge carries ionization and drift parameters are calculated in numerical net nodes for the current time step; 4) the system of equations (5) is solved by matrix factorization method taking into account the boundary conditions (2) and electron and hole concentration distributions are calculated for the new time step and than the calculation cycle is repeated for all time steps until the end of the time period; 5) the full current in external circuit is calculated. This process is continued from one period to another until the convergence is achieved by means of the results comparison for the two neighboring periods with the necessary precision. Then all harmonics of the external current, admittance for the harmonic number \( m \) and power characteristics can be calculated by the Fourier transformation.

3 Optimization Technique

The special optimization algorithm that combines one kind of direct method and a gradient method was used to optimize the output characteristics of DAR diode. To obtain the better solution for the optimum procedure, it is necessary to analyze \( N \)-dimensional space for \( N=5 \). The principal vector of optimization parameters consists of five variables \( y = (y_1, y_2, y_3, y_4, y_5) \), where the components will be defined below. The optimization algorithm can be defined by next steps:

1. Given as input two different approximations of two initial points \( y^0 \) and \( y^1 \).
2. At these points, we start with the gradient method, and have performed some steps. As a result, we have two new points \( y^{0\cdot} \) and \( y^{1\cdot} \). This process is reflected by the next equations:

\[
\begin{align*}
y^{0\cdot,n+1} &= y^{0\cdot,n} - \delta_n \cdot \nabla F(y^{0\cdot,n}), \\
y^{1\cdot,n+1} &= y^{1\cdot,n} - \delta_n \cdot \nabla F(y^{1\cdot,n}), \\
n &= 0, 1, ..., N-1 \\
Y^0 &= y^{0\cdot, N}, \quad Y^1 = y^{1\cdot, N},
\end{align*}
\]

where \( F \) is the cost function, and, \( \delta_n \) is the parameter of the gradient method.

3. We draw a line through two these points, and perform a large step along this line. We have a new point \( y^{s+1} \):

\[
y^{s+1} = Y^{s} + \alpha(Y^{s} - Y^{s-1}), \quad s = 1, \quad (8)
\]

where \( \alpha \) is the parameter of the line step.

4. Then we perform some steps from this point by the gradient method, to obtain a new point \( Y^s \):

\[
y^{s,n+1} = y^{s,n} - \delta_n \cdot \nabla F(y^{s,n}), \quad (9)
\]

\( s = s + 1 \), \( Y^s = y^{s,N} \).

Then step 3 and 4 are repeated with the next values of index \( s \) \((s = 2, 3, \ldots)\).

This optimization algorithm cannot find the global maximum of the cost function, but only a local one. To obtain the better solution of the optimum procedure, it is necessary to analyze \( N \)-dimensional volume with different initial points. During the optimization process, it is very important to localize the subspace of the \( N \)-dimensional optimization space for more detailed analysis. Then this subspace can be analyzed carefully.

4 Numerical scheme convergence

The numerical scheme for the problem (1) for the DDR IMPATT diode structures was produced some years ago [16]. The scheme analysis showed a very good convergence of the numerical model. The numerical algorithm convergence was obtained during 6–8 high frequency periods. The careful analysis of numerical model for the DAR diode with the doping profile in Fig.1 shows that the numerical scheme convergence for this type of the doping profile is very slow and the numerical transition process continues many periods to obtain the stationary mode.

The necessary number of the consequent periods depends on the diode width and operating frequency and changes from 30 – 50 for the frequency band 15 – 60 GHz up to 150 – 250 periods for 200 – 300 GHz. This very slow convergence was stipulated by the asynchronies movement of the electron and hole avalanches along the same drift region \( v \). It occurs owing to the different drift velocities of the carriers. This effect provokes a large number of necessary periods and large computer time. This is a specific feature of the analyzed type of diode structure.
5 Results and Discussion

The accurate analysis for DAR IMPATT diode has been made for different values of \( p \), \( n \) and \( v \) region width and the different donor and acceptor concentration level.

The analysis shows that the active properties of the diode practically are not displayed for more or less significant width of the region \( v \) [9]. The main reason of this effect is a non-synchronize mechanism of carriers’ movement along the drift region. This conclusion is contrary to results of the paper [7]. Our results display the active features of the DAR diode the same profile for some frequency bands when the \( v \)-region width less than 0.5 \( \mu m \).

We can decide that two superior bands appear as a result of the special conditions making for these bands. This effect gives possibility to use the second and the third bands for the microwave power generation of the sufficient level.

The DAR diode internal structure analysis has been provided for all three-frequency bands. The structure optimization for the second frequency band has been provided in [9]. The present paper describes the diode analysis for the third frequency band near 300 GHz for the feeding current density 50 kA/cm\(^2\) and 70 kA/cm\(^2\). The results of the analysis and small signal admittance optimization for third frequency band are shown in Fig. 2 for two current density values: 50 and 70 kA/cm\(^2\).

The cost function of the optimization process was selected as real part of the complex admittance. The set of the variables for the optimization procedure was composed from five technological parameters of the diode structure: two doping levels for \( p \) and \( n \) regions and three widths of \( p \), \( n \) and \( v \) regions. The optimal values of these parameters are next: doping levels of \( n \) and \( p \) zone are equal to 0.48 \( \times 10^{17} \) cm\(^{-3}\) and 0.36 \( \times 10^{17} \) cm\(^{-3}\) accordingly, the widths of the two corresponding areas are equal to 0.09 \( \mu m \) and 0.18 \( \mu m \), and the width of the drift \( v \)-region is equal to 0.32 \( \mu m \).

The active diode properties for all frequency bands are improved when the current density increases. More positive effect was obtained for the frequency 330 GHz because the optimization for this frequency.

The characteristics obtained for 330 GHz under a large signal serve as the main result. The amplitude characteristics of the conductance for this frequency are shown in Fig. 3 for two values of the current density.

![Figure 3. Conductance \( G \) dependency as functions of first harmonic amplitude \( U_1 \) for \( f = 330 \) GHz and for two values of feeding current density.](image)

The conductance characteristic is softer for current density 50 kA/cm\(^2\) because the diode structure optimization was provided for this current. The characteristics for 70 kA/cm\(^2\) are sharper but correspond to the larger conductance –\( G \).

The output power dependencies as a function of first harmonic amplitude \( U_1 \) for \( f = 330 \) GHz and for two values of feeding current are shown in Fig. 4.

![Figure 4. Output generated power \( P \) dependency as functions of first harmonic amplitude \( U_1 \) for \( f = 330 \) GHz and for two values of feeding current density.](image)
These amplitude characteristics show the possibility to obtain a sufficient level of output power near the 4 kW/cm².

6 Conclusion
The numerical scheme that has been developed for the analysis of the different types of IMPATT diodes is suitable for the DAR complex doping profile investigation too but in this case the numerical scheme convergence is slower. The diode structure optimization gives the possibility to improve the admittance characteristics for high frequency bands.

Acknowledgement
This work was supported by the Autonomous University of Puebla by the project VIEP 135/EXC/08-G.

References: