Comparative Analysis of DDR and DAR IMPATT Diodes

ALEXANDER ZEMLIAK, ANDREY OSTROVSKY, SANTIAGO CABRERA
Department of Physics and Mathematics
Puebla Autonomous University
Av. San Claudio y 18 Sur, Puebla, 72570
MEXICO

Abstract: - The comparative analysis of the well known Double Drift Region (DDR) IMPATT diode structure and the $n^{+}pvnp^{+}$ structure for the avalanche diode has been realized on basis of the drift-diffusion nonlinear model. The last type of the diode was named as Double Avalanche Region (DAR) IMPATT diode. This structure includes two avalanche regions inside the diode. The phase delay which was produced by means of two avalanche zones and one drift zone *v* is sufficient for the negative resistance obtained for the wide frequency region. The numerical model that is used for the analysis of various diode structures includes all principal features of the physical phenomena inside the semiconductor structure. The admittance characteristics of both types of the diodes were analyzed in very wide frequency region.

Keywords: - Semiconductor microwave devices, modelling and simulation, numerical methods.

1 Introduction

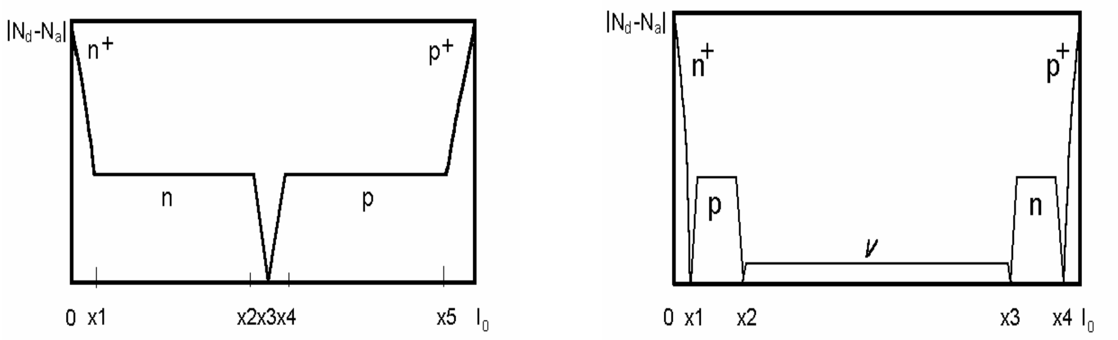
The problem of the microwave power generation of sufficient output level is an essential problem of modern semiconductor electronics. The IMPATT diode of different structures is the most powerful semiconductor device. The single drift region (SDR) and the double drift region (DDR) IMPATT diodes are very well known [1] and used successfully for the microwave power generation in millimeter region. The simulation and optimization of its parameters [2]-[4] give very high output power level and serves as the basis for the technology to produce the diodes with the extreme characteristics. From the beginning [5] the main idea to obtain the negative resistance was defined on 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. The transit time delay of both types of diodes is the essential factor of the necessary phase conditions fulfilment to obtain negative resistance. However a diode that has two avalanche regions can produce an avalanche delay which alone can satisfy necessary conditions to generate microwave power. In this case the phase delay of the drift zone becomes subsidiary. The DDR diode and the DAR diode can be defined by means of the following two structures *n+npp+* and *n+pvnp+* that are presented schematically in Fig. 1 (a), (b).

The DAR diode has two avalanche regions around n+p and np+ junctions and one common drift region. This type of diode was suggested in [6]. The characteristics of this diode type were analyzed in DC and RF modes [7]-[9]. Each of the avalanche zones provides the phase delay about p /2 being sufficient to produce negative diode resistance. The electric field distribution along the axis *x* for both types of diodes can be approximated by Fig. 2.

There is one avalanche zone for DDR diode and two avalanche zones for DAR diode. The authors of the works [6]-[9] affirm that the drift zone transit time delay is not a critical parameter for DAR diode because of the total avalanche delay equal to p . Some advantages of the DAR structure were prognosticated due to this fact. The analysis provided in these works gave the interesting and at the same time very surprising results concerning the main features of the DAR diodes. Some of these results were obtained by means of the small signal model [6]-[7]. Other results [8]-[9] were obtained on basis of simplified nonlinear model. We suppose that there is a necessity to analyze these structures on the basis of a precise model of the IMPATT diode which was developed in some works of the authors [10]-[11].

2 Numerical Model

The electrical model which is used for the precise analysis of the internal diode structure describes all important physical phenomena of the semiconductor device. This model is based on the system of two continuity equations for electrons and holes, the Poisson equation for the potential distribution in structure and necessary boundary conditions as for continuity equations and for the Poisson equation.



(a) (b)

Fig. 1. Doping profile for: (a) – DDR IMPATT diode, (b) – DAR IMPATT diode.

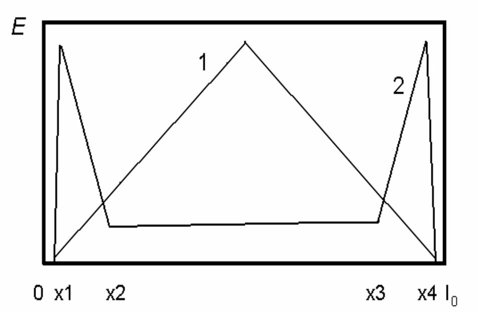


Fig. 2. Electric field distribution for DDR diode – 1 and DAR diode – 2.

The system of the continuity equations includes two differential equations for the carrier concentrations and two additional equations for current density determination. These equations are presented below in a normalized form:

$$\frac{\partial n(x,t)}{\partial t} = \frac{\partial J_n(x,t)}{\partial x} + \alpha_n \left| J_n(x,t) \right| + \alpha_p \left| J_p(x,t) \right|$$

$$\frac{\partial p(x,t)}{\partial t} = -\frac{\partial J_p(x,t)}{\partial x} + \alpha_n \left| J_n(x,t) \right| + \alpha_p \left| J_p(x,t) \right| \qquad (1)$$

$$J_n(x,t) = n(x,t)\, V_n + D_n \frac{\partial n(x,t)}{\partial x}$$

$$J_p(x,t) = p(x,t)\, V_p - D_p \frac{\partial p(x,t)}{\partial x}$$

where n, p are the concentrations of electrons and holes; J_n, J_p are the current densities; α_n, α_p are the ionization coefficients; V_n, V_p are the drift velocities; D_n, D_p are the diffusion coefficients. Ionization coefficients, drift velocities and diffusion coefficients are the functions of two arguments; the space coordinate x and the time t.

The dependences of the ionization coefficients α_n, α_p on field and temperature have been approximated using the approach described in [12]. The drift velocities and diffusion coefficients were calculated by means of approximations given in [13]. These approximations include all essential features of the carrier's mobility in silicon semiconductor and give possibility to calculate diode behavior in a wide frequency region for the different regimes.

The boundary conditions for this system include concentration and current definition for contact points and can be written as follows:

$$n(0,t) = N_D(0); \qquad p(l_0,t) = N_A(l_0);$$
$$J_n(l_0,t) = J_{ns}; \qquad J_p(0,t) = J_{ps}. \qquad (2)$$

where 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:

$$\frac{\partial E(x,t)}{\partial x} = -\frac{\partial^2 U(x,t)}{\partial x^2} = N_D(x) - N_A(x) + p(x,t) - n(x,t) \qquad (3)$$

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:

$$U(0,t)=0;\ \ U(l_0,t)=U_0+\sum_{m=1}^{M}U_m\, sin\left(w\, mt+j_m\right) \qquad (4)$$

where U_0 is the DC voltage on diode contacts; U_m is the amplitude of harmonic number m; w is the fundamental frequency; j_m is the phase of harmonic number m; M is quantity of harmonics.

Equations (1) - (4) adequately describe processes in the IMPATT diode in a wide frequency band. However the numerical solution of this system of equations is very difficult due to existing of a sharp dependence of equation coefficients on electric field. Evident numerical schemes have poor stability and require a lot of computing time for good calculation accuracy obtaining. It is more advantageous to use non-evident numerical scheme that has a significant property of absolute stability.

After approximation of functions and its differentials the system (1) is transformed to the non-evident modified Crank-Nicholson numerical scheme. This modification consists of two numerical systems each of them having three-diagonal matrix. This system has the following form:

$$\begin{aligned}
&-\left(a_n-b_n\right)\ n_{i-1}^{k+1}+\left(1+2a_n\right)\ n_i^{k+1}-\left(a_n+b_n\right)\ n_{i+1}^{k+1}= \\
&a_n\ n_{i-1}^{k}+\left(1-2a_n\right)\ n_i^{k}+a_n\ n_{i+1}^{k}+b_n\ \left(n_{i+1}^{k}-n_{i-1}^{k}\right)+ \\
&\qquad a_n\left|t\cdot V_n\cdot n_i^k+r\cdot D_n\cdot\left(n_{i+1}^k-n_{i-1}^k\right)\right|+ \\
&\qquad a_p\left|t\cdot V_p\cdot p_i^k-r\cdot D_p\cdot\left(p_{i+1}^k-p_{i-1}^k\right)\right|
\end{aligned} \qquad (5)$$

$$\begin{aligned}
&-\left(a_p+b_p\right)\ p_{i-1}^{k+1}+\left(1+2a_p\right)\ p_i^{k+1}-\left(a_p-b_p\right)\ p_{i+1}^{k+1}= \\
&a_p\ p_{i-1}^{k}+\left(1-2a_p\right)\ p_i^{k}+a_p\ p_{i+1}^{k}-b_p\ \left(p_{i+1}^{k}-p_{i-1}^{k}\right)+ \\
&\qquad a_p\left|t\cdot V_p\cdot p_i^k-r\cdot D_p\cdot\left(p_{i+1}^k-p_{i-1}^k\right)\right|+ \\
&\qquad a_n\left|t\cdot V_n\cdot n_i^k+r\cdot D_n\cdot\left(n_{i+1}^k-n_{i-1}^k\right)\right|
\end{aligned}$$

$i = 1, 2, \ldots\ I_1-1;\qquad k = 0, 1, 2, \ldots\infty$

where $a_{n,p}=\dfrac{t\ D_{n,p}}{2h^2};\ b_{n,p}=\dfrac{t\ V_{n,p}}{4h};\ \ r=\dfrac{t}{2h};$

i is the space coordinate node number; k is the time coordinate node number; h is the space step; t is the time step; I_1 is the space node number.

The approximation of the Poisson equation is performed using ordinary finite difference scheme at every time step k:

$$U_{i-1}^k-2U_i^k+U_{i+1}^k=h^2\left(N_{Di}-N_{Ai}+p_i^k-n_i^k\right) \qquad (6)$$

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; 2) the voltage distribution is calculated at every space point from the Poisson equation by factorization method [10], 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 and electron and hole concentration distributions are calculated for the new time step. After this the calculation cycle is repeated for all time steps until the end of the time period. This process is continued from one period to another until the convergence is achieved by means of the results comparison for two neighboring periods. Then all harmonics of the external current, admittance for the harmonic number m and power characteristics can be found by the Fourier transformation.

3 Numerical Scheme Convergence

The numerical scheme (5)-(6) characteristic analysis for different DDR IMPATT diode has been made some years ago [10]. This analysis showed a good convergence of the numerical model. The convergence was obtained during 6 – 8 periods.

The analysis of numerical model for the DAR type of the doping profile (Fig.1(b)) gave an unexpected but understandable result. The numerical scheme convergence for this type of the doping profile is very slow. The quantitative results of the numerical scheme convergence for the principal diode characteristic, DAR diode conductance as the period number function are shown in Fig. 3. The necessary number of the consequent periods depends on the operating frequency and can change from 30 – 50 for the frequency region 15 – 60 GHz up to 150 – 250 periods for 200 – 300 GHz. This very slow convergence is stipulated by the asynchronies movement of the electron and hole avalanches along

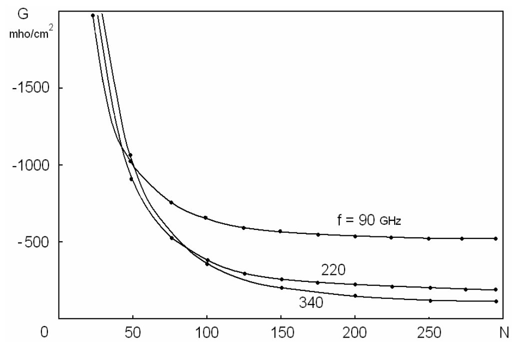


Fig. 3. Conductance as function of period number *N*.

the same transit time region *v*. It occurs owing to the different drift velocities of the carriers. This type of the numerical convergence provokes a large number of necessary periods and large computer time. We need to declare that the bad convergence result is the feature of the diode mathematical numerical scheme and is not the physical diode property. The physical stability is discussed more detail in the next section.

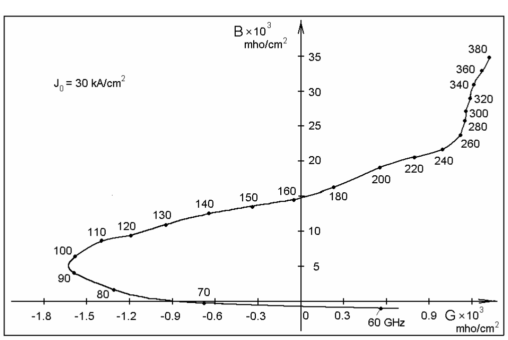
4 Comparative Analysis

The doping profile structures for the DDR and DAR IMPATT diode active layer are shown in Fig. 1. The technological characteristics of the DDR diode is defined by means of following parameters: the doping level of the *n*-zone and *p*-zone are equal to $1.5\cdot10^{17}$ cm^{-3}, the widths of the two corresponding areas are equal to 0.25 μm and 0.22 μm, accordingly, the width of *p*-*n* junction was given as 0.04 μm from the technological aspects. The DAR diode doping profile is the same as in paper [9] to provide the adequate comparison. The accurate analysis for both types of the diodes has been made for different value of *p*, *n* and *v* region width and the different donor and acceptor concentrations.

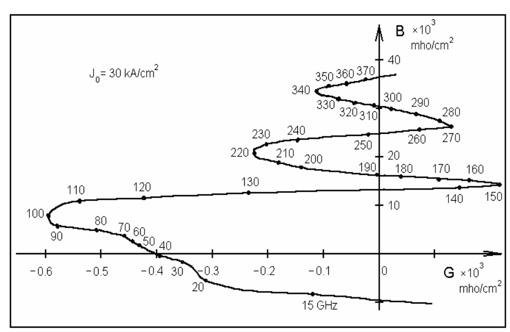
The average operating temperature *T* has been defined as 200 $^\circ C$. The analysis showed that for more or less significant width of the region *v* (more than 0.5 μm) the active properties of the diode do not show themselves. The reason is the same as for the slow mechanism convergence of the numerical model. The electron and hole avalanches have different transit velocities but they move along the same drift region *v*. It provokes different time delay for carriers during the transit region movement. The larger width of the region *v* makes delay time more different and the active properties are reduced. That is why we need to reduce the width of the region *v* to obtain necessary negative admittance. This conclusion is contrary to all results of the papers [8]-[9].

Another positive idea consists in non symmetric doping profile utilization. This profile gives some compensation to the asynchronies mechanism. Taking into account these considerations non symmetric doping profile diode was analyzed in a wide frequency range. We selected one optimized type of the diode doping profile for detail analysis. The main technological characteristics of this diode is defined by means of following parameters: the doping level of the *n*-zone is equal to $0.5\cdot10^{17}$ cm^{-3}, the doping level of the *p*-zone is equal to $0.2\cdot10^{17}$ cm^{-3}, the widths of the two corresponding areas are equal to 0.1 μm and 0.2 μm, accordingly, the width of the drift *v*-region is equal to 0.32 μm, the width of each *p*-*n* junction was given as 0.02 μm from the technological aspects. In Fig. 4 (a), (b) the small signal complex admittance is presented for the wide frequencies range for DDR and DAR diodes and for the current density J_0 = 30 kA/cm^2.

There are some differences of the DAR diode frequency characteristics from the classical DDR IMPATT diodes. First of all the new type of the



(a)



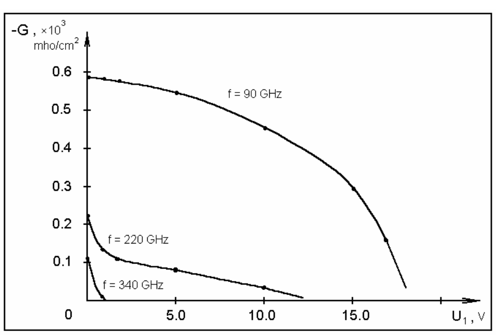
(b)

Fig. 4. Complex small signal admittance for different frequencies and two diode types: (a) – DDR, (b) –DAR.

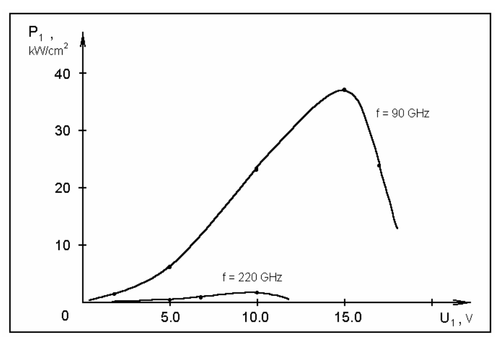
diode has three active bands in the millimetric range (Fig.4 (b)) and the DDR diode has only one band (Fig.4 (a)). The first active band of the DAR diode is very wide and covers frequency region from 12 to 138 GHz. The real part of the complex admittance *G* has negative value for the second and the third frequency bands too. This effect permits using another frequency bands, at least the second band, for the microwave power generation. The dependencies of conductance *-G* and generate power *P* as the function of the first harmonic amplitude U_1 are shown in Fig. 5 (a), (b) for different frequency bands and for the same value of the current density J_0 = 30 kA/cm^2. It is clear that the first band characteristic (*f* = 90 GHz) has a better behavior. The maximum value of the conductance *-G* is large and achieves nearly 600 mho/cm^2 under the small signal. The amplitude dependency for the first band is very soft and this provides a significant value of the generated power. Nevertheless the second and the third bands (for 220 GHz and for 340 GHz) have the perspective too. These characteristics have more sharp amplitude dependency and this effect limits the output power. However possible optimization of the diode internal structure can improve these characteristics and permits raise the power and the efficiency. The maximum power density is equal to 37 kW/cm^2 for the first frequency band (90 GHz) and 1.4 kW/cm^2 for the second one (220 GHz). The last result serves as the starting point for the DAR diode profile optimization to obtain maximum power generation for superior frequency bands.

The other important features of the DAR diode are the internal stability characteristics. The generator stability analysis can be done adequately only taking into account the oscillator system stabilized characteristics. However the comparison of the internal diode characteristics helps us to solve the problem of the best diode selection for the generator performance. The preliminary stability analysis has been provided on the basis of the diode admittance dependency study as the function of the feeding current density J_0 from 3 to 30 kA/cm^2. In Fig. 6 (a), (b) these dependencies are shown for the susceptance (Fig. 6 (a)) and for the conductance (Fig. 6 (b)) for both DAR and DDR diodes of the same frequency region. The susceptance dependencies are presented for three frequency bands for the DAR diode (solid lines) and for the frequency 90 GHz for the DDR diode (dash line). We can compare the two diode types of the last case. There is a more susceptance change for the DDR diode into the current density region 3 – 30 kA/cm^2. This change is equal to 1.91 times for the DDR diode and 1.26 for the DAR diode. It means that the DAR diode provides more frequency stability than the DDR diode when the feeding current density changes in a wide range. The large change of current density occurs for instance for the diode pulsed mode during front and back parts of the pulse.

The diode conductance as the function of the current density for both diode types and for the frequency 90 GHz is shown in Fig. 6 (b). The change of the conductance in the current density region 3 – 30 kA/cm^2 for the DDR diode is equal to 12.47 times and for the DAR – to 7.56 times. It means that the DAR diode has potentially more amplitude stability than the DDR diode. So, from the stability viewpoint the DAR diode has perspective with respect to the DDR diode because it has lesser variation both in the real and the imagine parts of the total admittance for a large current region.



(a)



(b)

Fig. 5. Conductance *G* (a) and generate power *P* (b) dependency as functions of first harmonic amplitude U_1 for different frequency zones.

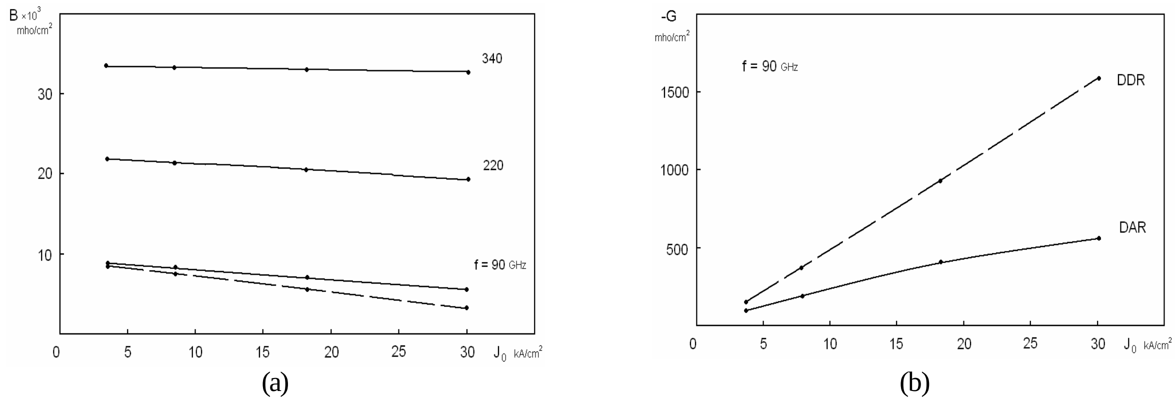


Fig. 6. Susceptance *B* (a) and conductance *G* (b) as functions of current density J_0 for DDR diode (dash line) and DAR diode (solid line).

5 Conclusions

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. Some new features of the DAR diode were obtained by the careful analysis based on the precise numerical model. The principal results were obtained by the accurate analysis and contradict to the data that have been obtained on basis of the approximate models of the DAR diode. These results show that the diode does not have the active properties for the sufficiently large intrinsic region. To obtain the negative conductance we need to reduce the intrinsic region. Nevertheless the diode has a wide first frequency band generation and two superior frequency bands with sufficient output power level. The DAR type of the IMPATT diode can be used for the output power generation in more wide frequency region than the DDR IMPATT diode.

References:

[1] Edited by Kai Chang, *Handbook of Microwave and Optical Components*, John Wile & Sons, N.Y., Vol. 2, 1990.

[2] K.V. Vasilevskii, Calculation of the Dynamic Characteristics of a Silicon Carbide IMPATT Diode, *Sov. Phys. Semicond.*, Vol. 26, 1992, pp. 994-999.

[3] C. Dalle, and P.A. Rolland, Drift-Diffusion Versus Energy Model for Millimetric-Wave IMPATT Diodes Modelling, *Int. J. Numer. Modelling*, Vol. 2, 1989, pp. 61-73.

[4] V. Stoiljkovic, M.J. Howes, and V. Postoyalko, Nonisothermal Drift-Diffusion Model of Avalanche Diodes, *J. Appl. Phys.*, Vol. 72, 1992, pp. 5493-5495.

[5] W.T.Read, A Proposed High-Frequency Negative Resistance Diode, *Bell Syst. Tech. J.*, Vol. 37, 1958, pp.401-446.

[6] B. Som, B.B. Pal, and S.K. Roy, A Small Signal Analysis of an IMPATT Device having two Avalanche Layers Interspaced by a Drift Layer, *Solid-State Electron.*, Vol. 17, 1974, pp. 1029-1038.

[7] D.N. Datta, and B.B.Pal, Generalized Small Signal Analysis of a DAR IMPATT Diode, *Solid-State Electron.*, Vol. 25, No. 6, 1982, pp. 435-439.

[8] S.P.Pati, J. Banerjee, S. Roy, High Frequency Numerical Analysis of Double Avalanche Region IMPATT Diode, *Semicond. Sci. Technol.*, Vol. 6, 1991, pp. 777-783.

[9] A.K. Panda, G.N. Dash, and S.P. Pati, Computer-Aided Studies on the Wide-Band Microwave Charactyeristics of a Silicon Double Avalanche Region Diode, *Semicond. Sci. Technol.*, Vol. 10, 1995, pp. 854-864.

[10] A. Zemliak, S. Khotiaintsev, and C. Celaya, Complex Nonlinear Model for the Pulsed-Mode IMPATT Diode, *Instrumentation and Development*, Vol. 3, No. 8, 1997, pp. 45-52.

[11] A. Zemliak, and R. De La Cruz, An Analys is of the Active Layer Optimization of High Power Pulsed IMPATT Diodes, *Comput. & Systems*, Spec. Edit., Dec. 2002, pp. 99-107.

[12] W.N. Grant, Electron and Hole Ionization Rates in Epitaxial Silicon at High Electric Fields, *Solid-State Electronics*, Vol.16, No.10, 1973, pp.1189-1203.

[13] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, A Review of Some Charge Transport Properties of Silicon, *Solid-State Electron.*, Vol. 20, 1977, pp. 77-89.