Doping Profile Optimization of DDR Pulsed-Mode IMPATT Diode

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Abstract: - One of the main problems of high-power microwave semiconductor electronics is design and construction of a generator with extraordinary energy characteristics. One of the solution of this problem is to use the pulsed-mode operation. Modern semiconductor technology provides the possibilities for the fabrication of submicron structures with a complex doping profile. This gives an opportunity to design special IMPATT diode structures for pulsed-mode operation having high feed current values.

In this work, on the base of numerical model that includes precise electrical and thermal submodels, the extremely energy characteristics of an Si double-drift pulsed-mode IMPATT diodes for 94 GHz and 140 GHz are investigated. The optimization of the internal structure of the diode with a traditional doping profile and with complex doping profile is provided.

The optimization algorithm was designed as the combination of one kind of direct method and a gradient method. This method is more successful for the optimization of millimetric wave devices because the objective function of that type of device as a function of its arguments has a very complex behavior in N-dimensional space.

Semiconductor structures with a complex doping profile are analyzed for improving the power level and efficiency of a pulsed-mode IMPATT diode with a maximum level of permanent current density. The dependencies of power level, efficiency, and admittance have been investigated as functions of feeding current density I_0 for the optimum structure and for near optimum ones.

One of the important problems for the real type of the complex doping profile diode optimization is the sensibility analysis of energy characteristics for various geometrical sizes and doping levels. This analysis shows that the variation of the total diode length around the optimal value leads to a great deterioration of the energy characteristics. On the other hand, the redistribution of the separate parts between the high and low doping profile parts within 20% has not led to a great decrease of the output power level.

Diode active layer optimization shows that the complex doping profile diode has a 1.25 - 1.4 times greater efficiency coefficient with respect to the permanent doping profile diode.The IMPATT diode with complex doping profile provides a maximum output power level and efficiency coefficient with a smaller value of feed current density.

These complex semiconductor structures may be recommend for the increase of a real time work period and the reliability of power pulsed-mode IMPATT diodes.

Key-Words: - IMPATT diode, modeling and simulation, structure optimization.
CSCC'99 Proceedings: - Pages 1851-1857

1 Introduction

Pulsed-mode IMPATT diodes that are utilized in microwave electronics have most frequently double-drift structures similar to the continuous-mode ones. The idea to use a special form of doping profile for the diode semiconductor structure has been realized in some works [1-3]. Modern semiconductor technology provides the possibilities for the fabrication of submicron structures with the complex doping profile. This gives one opportunity to design special IMPATT diode structures for pulsed-mode operation having high feed current values. That is very important for this operation mode because pulse mode can be provided extreme power value for this type of diode and for all microwave semiconductor devices in general.

In this work, the extreme energy characteristics of Si double-drift pulsed-mode IMPATT diodes for 94 GHz and for 140 GHz are investigated. The optimization of the internal structure of the diode with a traditional doping profile, Fig. 1, curve 1 and with a complex doping profile Fig. 1, curve 2 is provided. We have marked special points of curve 2 on the longitudinal axis for the determination of different technological lengths that are independent parameters of the optimization procedure. The sensitivity of the optimal diode structure's energy characteristics with respect to technological errors is determined too.

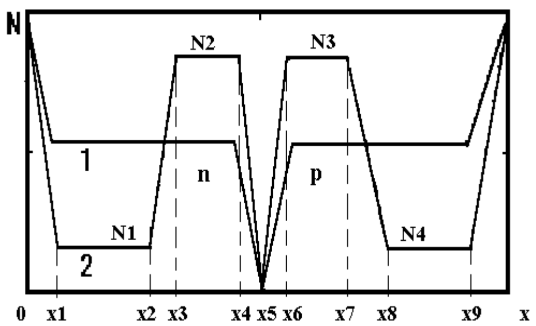


Fig. 1 Doping profile for two types of IMPATT diodes: 1 - typical diode structure, 2 - complex diode structure. $x1$,$x2$, ...,$x9$ are important technological lengths.

2 Numerical Model

The complex model consists of an electrical model that is based on the solution of the continuous equations system (1) jointly with one dimensional Poisson equation and the thermal model that is based on the solution of heat-conductivity equation (2).

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

$$J_n(x,t) = n(x,t)\, V_n + D_n \frac{\partial n(x,t)}{\partial x}$$
$$J_p(x,t) = p(x,t)\, V_p - D_p \frac{\partial p(x,t)}{\partial x}$$
$$\frac{\partial T}{\partial t'} = \frac{k}{\rho C} \Delta T + \frac{1}{\rho C} Q\,(x,t',T) \qquad (2)$$

where Δ is the two dimensional Laplace operator for cylindrical coordinate system

$$\Delta T = \frac{\partial^2 T}{\partial x^2} + \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r} \right)$$

r is the radial coordinate; x is the longitudinal coordinate; T is the Kelvin temperature; ρ is the material density; C is the specific thermocapacity; k is the thermoconductivity coefficient; $Q\,(x,t',T)$ is the internal heat source that has a dependency from electrical field, current density, and temperature.

Numerical solution of the main system (1) has been obtained by the modification of Crank-Nicolson numerical scheme and has a significant property of absolute stability.

Numerical solution of equation (2) is performed by the iteration method of alternating directions. This model is different from the ones in [4,5] because all electrophysical parameters are functions of electric field and temperature at a corresponding point of semiconductor structure, and because this model describes the heat source as a function of electric field intensity inside the diode structure. It is very important to take into account the temperature dependency because, just for pulse mode, there is a high level of permanent and alternative currents, and therefore the high level variation of temperature in time.

Numerical solution of the main system (1) has been obtained by the modification of Crank-Nicolson numerical scheme that is the basis of the work [6], and that has a significant property of absolute stability.

One of the principal characteristics of the optimization procedure is the computer time for one probe of objective function. Since one probe of the objective function includes the total analysis of IMPATT diode, it is very important to reduce the complete diode analysis time. The complex diode model [6] is based on the simultaneous using of electronic field and thermal models. This model has a great accuracy, but is complicated too, and therefore its functioning is too slow for the optimization problem.

Other model that was proposed in work [7] is more suitable just for optimization problem because this model has computer time for one probe significantly less than the model [6]. This model utilizes the Fourier series analysis, and therefore has limitation which inherent in this technique; in particular this model can be used for the stationary process analysis only. This model had been used successfully for the optimization of different types of IMPATT diodes.

The IMPATT diode thermal model is based on the numerical solution of a nonlinear thermoconductivity equation (2) for silicon crystal, contact planes, and heat sinks. It determines instantaneous semiconductor structure temperature at any point within the device for any given time moment. The thermal model that is described here has been utilized for the determination of temperature distribution in the diode structure having different types of doping profile. We have been used the second order of numerical approximation scheme for the equation (2). For this equation the alternating direction implicit method can be expressed in compact form as:

$$\frac{T_{i\ j}^{s+\frac{1}{2}} - T_{i\ j}^{s}}{t} = \frac{k}{r\ C}\left(\Lambda_1 T_{ij}^{s+\frac{1}{2}} + \Lambda_2 T_{ij}^{s}\right) + \frac{1}{r\ C} Q_j^{s}$$

$$\frac{T_{i\ j}^{s+1} - T_{i\ j}^{s+\frac{1}{2}}}{t} = \frac{k}{r\ C}\left(\Lambda_1 T_{ij}^{s+\frac{1}{2}} + \Lambda_2 T_{ij}^{s+1}\right) + \frac{1}{r\ C} Q_j^{s+\frac{1}{2}} \qquad (3)$$

$i = 1,2, \ldots I_2 - 1; \quad j = 1,2,\ldots J-1; \quad s = 0,1,2,\ldots\infty;$

where i, j are space coordinate numbers, s is the time coordinate number, Λ_1 is the partial numerical Laplace operator on the direction r, Λ_2 is the partial numerical Laplace operator on the direction x. Two these operators are defined on the standard five points numerical pattern. We solve the system (3) by the tridiagonal algorithm for the radial and longitudinal directions.

3 Optimization procedure

The optimization algorithm was designed as the combination of one of kind of direct method and a gradient method. This is one of the modification of well-known algorithm, which is successfully used for function with complicate structure.This method is more precisely successful for the optimization of millimetric wave devices because the objective function of that type of devices as the function of its arguments has a very complex behavior similar to a one "valley" in N-dimensional space. The objective function can be determined as the maximum electronic power, for example. The number of free variables for our case is equal to 8. These are four lengths *L1=x2-x1*, *L2=x4-x3*, *L3=x7-x6*, *L4=x9-x8* and four levels *N1*, *N2*, *N3*, *N4* of diode doping profile. We have been formed the principal vector of variables $y=\{y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8\}$ for these eight parameters of semiconductor structure.

The optimization algorithm consists of the next steps:

1. Given as input two different approximations of two initial points: y^0 and y^1.
2. At these points, we start by gradient method, and have performed some steps. As a result, we have two new points Y^0 and Y^1.

$$y^{0n+1} = y^{0n} - d_n \cdot \nabla F\left(y^{0n}\right),$$
$$y^{1n+1} = y^{1n} - d_n \cdot \nabla F\left(y^{1n}\right),$$
$$n = 0,1,\ldots N-1,$$

$$Y^0 = y^{0N}, \qquad Y^1 = y^{1N},$$

where F is the objective function, d_n is the parameter of the gradient method.

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

$$y^{s+1} = Y^s + a\left(Y^s - Y^{s-1}\right), \qquad s=1,$$

where a is the parameter of the line step.

4. Than we perform a some steps from this point by the gradient method, and obtain a new point Y^s.

$$y^{s\,n+1} = y^{s\,n} - d_n \cdot \nabla F\left(y^{s\,n}\right), \qquad s=s+1,$$
$$Y^s = y^{s\,N}.$$

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

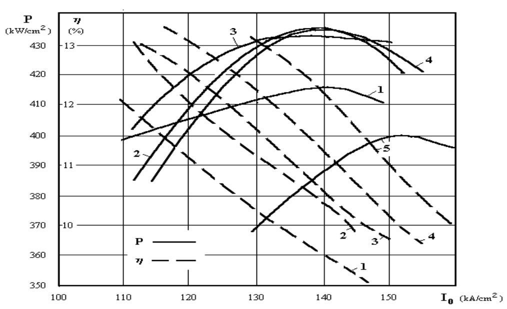
The optimization process that is presented above cannot find the global minimum of the objective function, but only a local one. To obtain the confidence that we have the better solution of the optimum procedure, it is necessary to investigate N-dimensional space with different initial points. In that case, it is possible to investigate N-dimensional volume in more detail. During the optimization process, it is very important to localize the subspace of the N-dimension optimization space for more detail analysis. N-dimensional space volume of independent parameters is determined approximately on the base of the model [7] for the first stage of optimization procedure. In that case, a Fourier series approximation of principal functions is used and because of this approximate model, we have a ten times acceleration. After that, on the basis of the precise model [6] we have analyzed the internal structure of two types of silicon diode for 3 and 2 mm region. One of these structures is an ordinary structure, and the other is a complex one.

4 Results

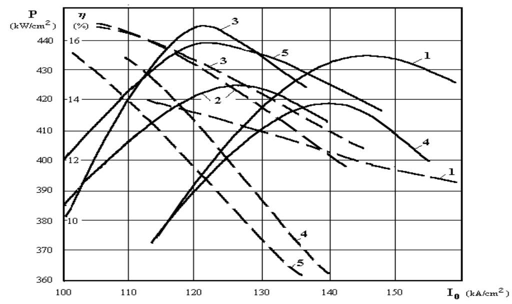
The complex type of the double-drift IMPATT diode active layer is shown in Fig.1, curve 2. The width of the p-n junction was given as 0.15 mm and 0.12 mm for 94 GHz and for 140 GHz respectively from the technological aspects. This type of doping profile provides a concentration of electrical field within the p-n junction. For the diode with a permanent doping level the following equalities are corrected: *N1=N2* and *N3=N4*. In that case, we have only four parameters for the optimization procedure: two lengths *L1=x4-x1*, *L2=x9-x6* and two doping levels *N1*, *N3*.

4.1 94 GHz Diode

In Fig.2 (a,b) the characteristics of power-level and efficiency for the permanent profile diode and complex profile diode for 94 GHz are presented as functions of feeding current density I_0 for the optimum structures and for others that are near the optimum.



(a)



(b)

Fig. 2 Output power *P* and efficiency coefficient *m* as functions of the feeding current density I_0 for optimum and near optimum structures with (a) permanent and (b) complex doping profile diode.

Structure 2 in Fig. 2a has the maximum power level 436 kW/cm^2 and optimal current density value I_0 = 140 kA/cm^2. In that case the efficiency is equal to 10.7 % for the maximum power point. Structure 5 has a maximum efficiency as the function of the current I_0, but for optimum power point this value no larger than for structures 2, 3 and 4. Besides, for this structure it is necessary to increase the current value until 153 kA/cm^2 for the obtaining of the optimum power point.

Semiconductor structures with a complex doping profile are analyzed for the improving of the power level and efficiency of pulsed-mode IMPATT diode. In that case eight parameters have been varied: *L1, L2, L3, L4, N1, N2, N3, N4*. Structure 3 is the optimal one. In this case the power level is 446 kW/cm^2 and optimal current density value is 123 kA/cm^2. Others structures are near this optimum one but have more low power level and efficiency. The extension of doping level high parts (structure 1) or increasing this level (structure 4) results to moving the power curve to the greater current density.

Comparison of the optimal characteristics for two different types of the structures as the permanent doping profile (curve 2, Fig. 3) and complex doping profile (curve 3, Fig. 4) shows that the maximum output power level is quasi equal for two these optimal structures (436 kW/cm^2 and 446 kW/cm^2), but efficiency coefficient has more difference (10.7% and 14.4%). The most important fact is a significant decrease of optimal value of permanent current density for the complex doping structure. For the permanent doping structure the optimal current density value is 140 kA/cm^2 but for the complex doping structure is 123 kA/cm^2. Therefore the complex doping profile structure has better energy characteristics.

4.2 140 GHz Diode

In Fig.3 (a,b) the characteristics of power-level, efficiency, and the real and imagine parts of complex admittance of the permanent profile 140 GHz diode are presented as functions of feeding current density I_0 for the optimum structures and for others that are near the optimum.

Structure 4 has the maximum power level of 430 kW/cm^2 and an optimal current density value of I_0 = 285 kA/cm^2. In that case, the efficiency is equal to 8.0 % for the maximum power point.

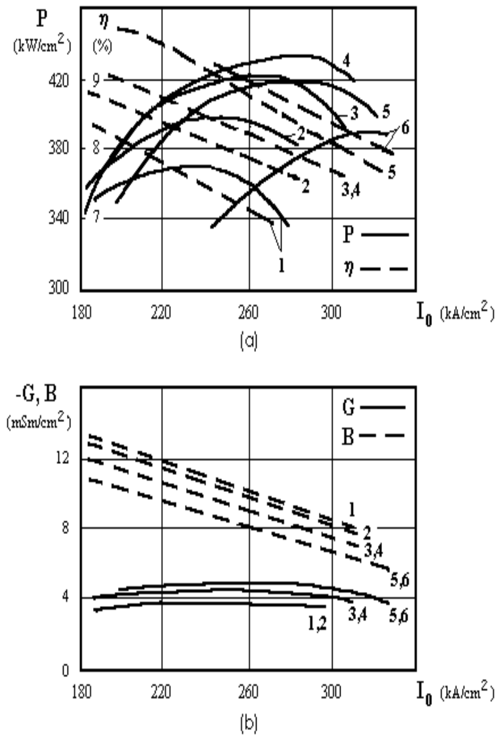


Fig. 3 (a) Output power *P* and efficiency coefficient *m* and (b) real *G* and imagine *B* parts of the total admittance as functions of feeding current density I_0 for optimal and near optimal structures with even doping profile level.

Structure 5 has a maximum of the negative real admittance and efficiency (8.5 %), but has a smaller power level because the doping level is high, and therefore the permanent voltage and first harmonic amplitude voltage are smaller. Structure 6 has a maximum efficiency as the function of the current I_0, but for optimum power point, this value is less then for structures 4 and 5. Besides, for this structure, it is necessary to increase the current value until 320 kA/cm^2 to obtain the optimum power point. Structures 5 and 6 have the maximum value of the real part of the total admittance, but have a greater doping level, and therefore a smaller value of the permanent and variable voltage and output power.

Semiconductor structures with a complex doping profile are analyzed for improving the power level and efficiency of a pulsed-mode IMPATT diode with the maximum level of permanent current density. In that case, eight parameters have been varied: *L1, L2, L3, L4, N1, N2, N3, N4*. In Fig. 4 (a, b) the dependencies of power level, efficiency and admittance are presented as functions of feeding current density I_0 for the optimum structure and for near optimum ones.

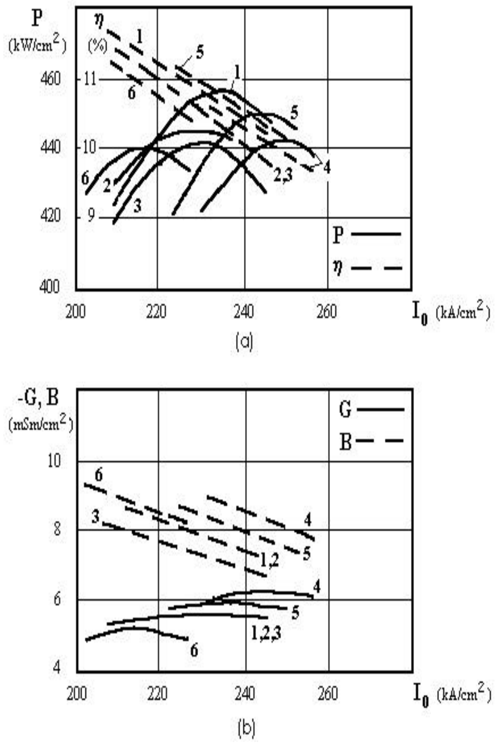


Fig. 4 (a) Output power *P* and efficiency coefficient *m* and (b) real *G* and imagine *B* parts of the total admittance as functions of feeding current density I_0 for optimal and near optimal structures with complex doping profile level.

Structure 1 is the optimal one. In this case, the power level is 457 kW/cm^2 and optimal current density value is 235 kA/cm^2. Others structures are near this optimum one but have more low power level and efficiency. The extension of doping level high parts (structures 4,5) results to moving the power curve to the greater current density. It is very important to compare the optimal characteristics for the two different types of structures as the permanent doping profile (curve 4, Fig. 2(a)) and the complex doping profile (curve 1,

Fig. 3(a)). A comparative analysis shows that the maximum output power level is quasi equal for two these optimal structures (436 kW/cm^2 and 452 kW/cm^2), but efficiency coefficient has more difference (8.5% and 10.7%). The most important fact is a significant decrease of optimal value of permanent current density for the complex doping structure. For the permanent doping structure, the optimal current density value is 285 kA/cm^2, but for the complex doping structure is 235 kA/cm^2. Therefore the complex doping profile structure has better energy characteristics, and allows the possibility to exploiting the diode under easier conditions.

One of the important problem for the real type of the complex doping profile diode optimization is the sensibility analysis of energy characteristics for various geometrical sizes and doping levels. The results of the investigation of an optimal structure by changing the doping profile levels *N1, N2, N3, N4* and lengths *L1, L2, L3, L4* within 20% around the optimal structure have been obtained. The diode doping profile level increase within 20% with respect to optimal structure leads to a small decrease of output power. On the other hand the diode's doping profile level decrease leads to a great decrease of output power.

Analysis of the diode structures with different lengths shows that the variation of the total length *L = x9-x1* around the optimal value leads to a great deterioration of energy characteristics. On the other hand the redistribution of separate part's dimensions between high and low doping profile parts within 20% has not been led to a great decreasing of the output power level.

5 Conclusion

Diode active layer optimization shows that the complex doping profile diode has a 6 % greater output power level and a 1.25-1.4 times greater efficiency coefficient with respect to the permanent doping profile diode. The IMPATT diode with the complex doping profile has an appreciable gain with respect to the permanent doping profile diode. This allows the possibility to obtain the maximum output power level with a smaller value of feed current density. The important feature of the optimal diode structure with a complex doping profile is a low sensitivity of the energy characteristics to the technological errors of the internal semiconductor structure. These complex semiconductor structures may be recommend for the increase of a real-time work period and the reliability of power pulsed-mode IMPATT diodes.

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