New expressions for non-punch-through and punch-through abrupt parallel-plane junctions based on Chynoweth law

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Abstract: The relations among the breakdown voltage, the width and the concentration of the voltage-sustaining layer for the non-punch-through (NPT) and punch-through (PT) abrupt parallel-plane junctions have been re-established based on the ionization integral by the Chynoweth model, distinguished from the conventional results obtained by the Fulop model. The numerical calculation results indicate that the new expressions are more accurate than those in previous literature. While the breakdown voltage of the NPT case varied from 400 to 1600 V using the Chynoweth model, the value using the Fulop model is overestimated by 12% (478 V) to 18% (1895 V). For the PT case with optimum design of the specific on-resistance, when the breakdown voltage is varied from 400 to 1600 V, the width and concentration are from 81.0168% to 80.2416% and from 91.4341% to 91.6941% of those of the NPT cases, respectively. The relations between the specific on-resistance and the breakdown voltage for both the NPT and PT structures are also established. Simulation results by MEDICI show good agreement with the proposed expressions.

Key words: abrupt parallel-plane junction; impact ionization integral; Chynoweth law; Fulop law

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1. Introduction

The tradeoff between the specific on-resistance (R_{on}) and breakdown voltage (BV) of the power devices has drawn much attention[1–9]. Most of the relationships between R_{on} and BV are calculated in closed form thanks to the Fulop formula, i.e., the power law approximations of the impact ionization coefficients[10], while it is known that Chynoweth's law[11], which is customarily used for device simulations by MEDICI, is more accurate to depict the real devices.Thus, the conventional design rulesby the Fulop modelfor the non-punch-through (NPT) or punch-through (PT) abrupt parallel-plane junction, which is the main voltage-sustaining region of some power devices, will get larger error compared to the numerical results inMEDICI simulations. Nonetheless, hardly any literature has focused on this problem.

The purpose of this paper is to propose new design expressions for the parameters in the NPTand PT abrupt parallel-plane junctions by Chynoweth's law. Firstly, a simplification of the ionization integral for both the NPT and PT structures is derived. Furthermore, the relationship between the breakdown voltage BV_{pp} of the NPT structure and its voltage-sustaining layer parameters, i.e., doping concentration N_{pp} and depth W_{pp}, is numerically calculated. The case to design the PT structure for the optimum $R_{on,pt}$ is also presented. Finally, the relations between R_{on} and BV for these two cases are proposed.

2. Simplification of the ionization integral with Chynoweth's law

The breakdown behavior of a p–n junction can begoverned by

$$I_n = \int \alpha_{n,ii} \exp\left[-\int^{w} (\alpha_{n,ii} - \alpha_{p,ii})\, dv\right] dw = 1. \quad (1)$$

where v and w are distances along the electric field line, and by Chynoweth's law, the impact ionization rates of electron and hole are $\alpha_{n,ii} = \alpha_n \exp\left(-\frac{b_n}{E}\right)$ with $a_n = 7.03 \times 10^5$ cm^{-1} and $b_n = 1.231 \times 10^6$ V/cm, and $\alpha_{p,ii} = a_p \exp\left(-\frac{b_p}{E}\right)$ with $a_p = 1.582 \times 10^6$ cm^{-1} and $b_p = 2.036 \times 10^6$ V/cm[12], respectively, where E is the electric field along the electric field line. For either the NPT or PT structure, it is obvious that the direction of the electric field line is the same as x direction, and thus E can be degenerated into a linear function $E(x) = k_0 x + E(0)$. Accordingly, the integral of $\alpha_{n,ii}$

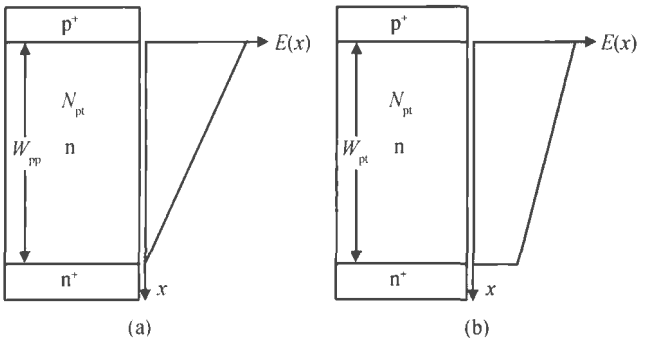

Fig. 1. Cross-sectional structures and their electric field profiles $E(x)$. (a) The NPT abrupt parallel-plane junctions. (b) The PT abrupt parallel-plane junctions.

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or $\alpha_{p,ii}$ in Eq. (1) can be expressed as the exponential integral function Ei(x) (here Ei(x) = $\int_{-\infty}^{x} \frac{e^t}{t} dt$ for $x < 0$), and $F(x) = \int_0^x (\alpha_{n,ii} - \alpha_{p,ii}) dx$ yields

$$F(x) = x\left[a_n \exp\left(-\frac{b_n}{k_0 x + E(0)}\right) - a_p \exp\left(-\frac{b_p}{k_0 x + E(0)}\right)\right] + \frac{a_n}{k_0}\left[b_n \mathrm{Ei}\left(-\frac{b_n}{k_0 x + E(0)}\right) + E(0)\exp\left(-\frac{b_n}{k_0 x + E(0)}\right)\right] - \frac{a_p}{k_0}\left[b_p \mathrm{Ei}\left(-\frac{b_n}{k_0 x + E(0)}\right) + E(0)\exp\left(-\frac{b_n}{k_0 x + E(0)}\right)\right] - A, \quad (2)$$

where $A = \frac{a_n}{k_0}[b_n \mathrm{Ei}(-\frac{b_n}{E_0}) + E(0)\exp(-\frac{b_n}{E_0})] - \frac{a_p}{k_0}[b_p \mathrm{Ei}(-\frac{b_p}{E_0}) + E(0)\exp(-\frac{b_p}{E_0})]$. The ionization integral in Eq. (1) can now be simplified as $I_n = \int_0^W \alpha_{n,ii} \exp[-F(x)]dx = 1$. It is noted that there are three unknown parameters in the design of the NPT or PT structure, i.e., BV, W and N. For a required breakdown voltage, although the relation of the concentration versus the width is hardly to be found in closed formas that by using the Fulop model, it can be numerically solved by MATLAB, in which the ionization integral is calculated by the trapezoid numerical method similar as that in Ref. [13].

3. Relation of the breakdown voltage, width and doping concentration for the NPT structure

For the NPT structure in Fig. 1(a), the electric field located at $x = W_{pp}$ is zero; then,the electric field can be calculated as $E(x) = \frac{qN_{pp}(W_{pp} - x)}{\varepsilon_s} = \frac{2BV_{pp}(W_{pp} - x)}{W_{pp}^2}$, where q and ε_s have their common meanings and $BV_{pp} = \frac{qN_{pp}W_{pp}^2}{2\varepsilon_s}$ is used. Thus, only two independent parameters are to be determined when solving the simplified integral equation. By using the simplified method proposed above, the relations among the doping concentration N_{pp}, the width W_{pp} and the given breakdown voltage BV_{pp} can be numerically calculated, which can benumerically fitted by

$$N_{pp} \approx 1.202 \times 10^{18} BV_{pp}^{-1.292} \quad \mathrm{cm}^{-3}, \quad (3)$$

$$W_{pp} \approx 0.03319 BV_{pp}^{1.146} \quad \mu\mathrm{m}, \quad (4)$$

$$W_{pp} \approx 4.322 \times 10^{14} N_{pp}^{-0.8927} \quad \mu\mathrm{m}. \quad (5)$$

Then the critical electric field, with the value $E_{c,pp} = qN_{pp}W_{pp}/\varepsilon_s$, can be determined as

$$E_{c,pp} \approx 5311 N_{pp}^{0.1139} \quad \mathrm{V/cm}. \quad (6)$$

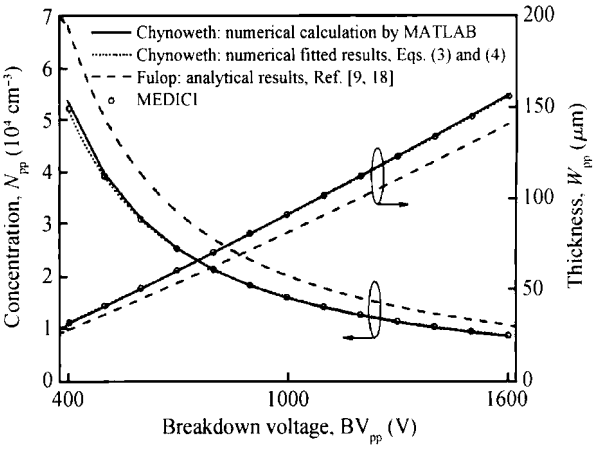

Fig. 2. The comparison of the relations of N_{pp} and W_{pp} versus BV_{pp} for the NPT structure.

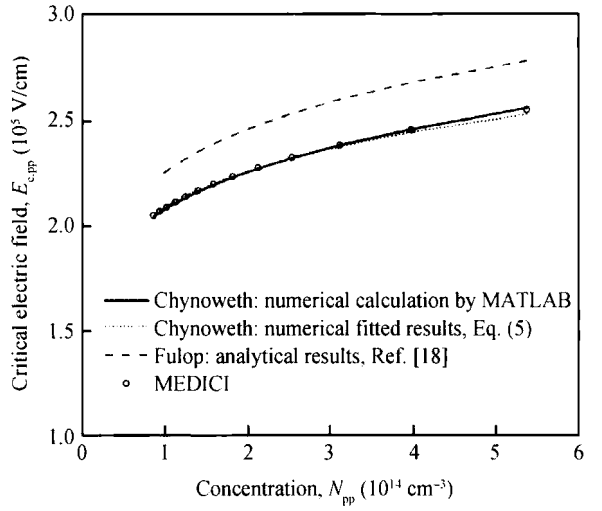

Fig. 3. The comparison of the relations of $E_{c,pp}$ versus N_{pp} for the NPT structure.

Figure 2 shows the comparison of the numerical and fitted results by MATLAB using the Chynoweth model, the analytical results using the Fulop model, and the simulation results from MEDICI. It is seen that, for the same breakdown voltage BV_{pp}, the concentration N_{pp}, which is $N_{pp} \approx 2.01 \times 10^{18} BV_{pp}^{-4/3}$ cm^{-3}[9, 18] is larger than that estimated in Eq. (3), and the width W_{pp} from the Fulop model, which is $W_{pp} \approx 0.0257 BV_{pp}^{7/6}$ μm[9, 18], is smaller than that in Eq. (4). That is to say, the breakdown voltage calculated from the Fulop model is larger than that from the Chynoweth model provided that the same concentration is given. For BV_{pp} varied from 400 to 1600 V by the Chynoweth model, the value is overestimated by 12% (478 V) to 18% (1895 V) by the Fulop model. This is due to the fact that the impact ionization rate determined by the Fulop model is smaller[16], which leads to a higher critical electric field determined by $E_{c,pp} \approx 4010 N_{pp}^{1/8}$ V/cm[18] shown in Fig. 3 and a bigger breakdown voltage for the same doping.

In the MEDICI simulation, for simplicity, the impact ionization integral is calculated by ignoring the effect of the ionization-generated carriers, and the number of carriers in the simulation is zero. In the calculation of the R_{on}, the carrier mobility model of ANALYTIC with its default setting is used. The

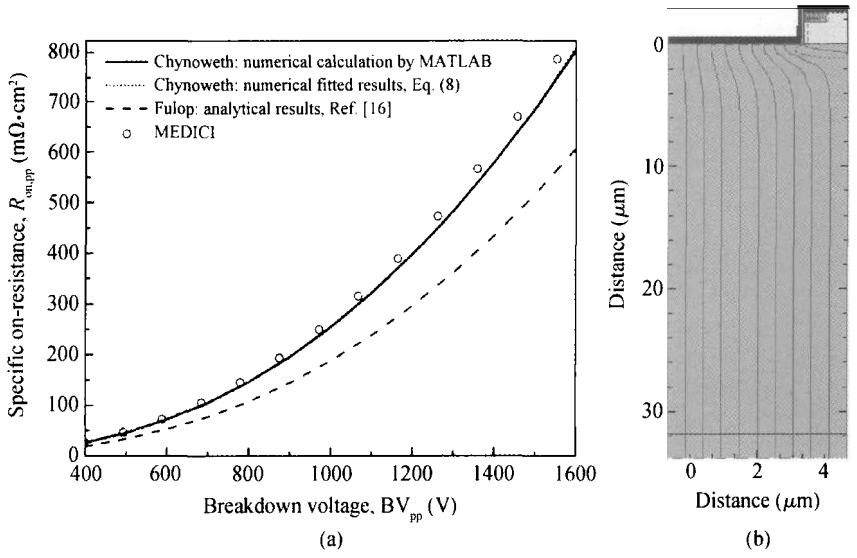

Fig. 4. The comparison of the design expressions by Chynoweth and Fulop models. (a) The comparison of relations of $R_{on,pp}$ versus BV_{pp} for the NPT structure. (b) The simulated 400-V trench NPT VDMOSFET.

simulation results of the breakdown voltage BV_{pp} and the critical electric field $E_{c,pp}$ show that the numerical results as well as their approximation expressions are in excellent agreement.

The specific on-resistance of the NPT case is calculated by $R_{on,pp} = W_{pp}/q\mu_n N_{pp}$, where the concentration-dependent mobility μ_n is modeled by the Caughey-Thomas formulation[14, 15]

$$\mu_n = 55.24 + \frac{1373.99}{1 + \left(\frac{N}{1.072 \times 10^{17}}\right)^{0.73}}. \quad (7)$$

Then, the specific on-resistance $R_{on,pp}$ for a given breakdown voltage BV_{pp} can be numerically fitted as

$$R_{on,pp} \approx 9.6161 \times 10^{-6} BV_{pp}^{2.473} \quad m\Omega \cdot cm^2. \quad (8)$$

The relation $R_{on,pp} \approx 5.93 \times 10^{-6}\ BV_{pp}^{2.5}$ mΩ·cm^2 by the Fulop model in Ref. [16] is smaller than that estimated in Eq. (8), which is shown in Fig. 4(a). For BV_{pp} varied from 400 to 1600 V, the $R_{on,pp}$ estimated in Eq. (8) is varied from 25.93 to 802.09 mΩ·cm^2, whereas the value by the Fulop model is underestimated by 26.8% (18.98 mΩ·cm^2) to 24.3% (607.23 mΩ·cm^2). The simulation results from MEDICI are also shown in this figure. A simulated 400-V trench NPT VDMOSFET is shown in Fig. 4(b). The gate oxide thickness and p-channel doping are 40 nm and 1×10^{17} cm^{-3}, respectively. For a required breakdown voltage, the doping and width of the drift region are given by Eqs. (3) and (4), respectively. The simulated threshold voltage (V_{th}) is about 2 V, and the applied gate-to-source (V_{GS}) and drain-to-source (V_{DS}) voltages are 15 V and 1 V, respectively. The simulation results show good agreement with the results from Eq. (8). The slight deviation of the breakdown voltages is mainly because Eqs. (3) and (4) are derived from the ideal abrupt NPT junctions, which are different from the simulated trench NPT VDMOSFETs in Fig. 4(b).

4. Relation of the breakdown voltage, width and doping concentration for the optimized PT structure

For the PT case, the electric field can be written as $E(x) = -\frac{qN_{pt}x}{\varepsilon_s} + \left(\frac{qN_{pt}W_{pt}}{2\varepsilon_s} + \frac{BV_{pt}}{W_{pt}}\right)$, and three independent parameters are to be determined in the solution of the integral equation. For a given breakdown voltage BV_{pt}, the relation of the concentration N_{pt} versus the width W_{pt}, which is shown in Fig. 5, can be calculated by using the above same method. Specifically, the NPT case, which is the edge of the PT case, is also shown in this figure.

For a given BV_{pt}, one group of W_{pt} and N_{pt} in Fig. 5 will lead to the minimum $R_{on,pt}$, which can also be calculated by the Caughey-Thomas model. Then, the relation of N_{pt} and W_{pt} for the optimized PT structure to minimize $R_{on,pt}$ with different BV_{pt} can be numerically fitted as

$$W_{pt} \approx 2.875 \times 10^{-2} BV_{pt}^{1.136} \quad \mu m, \quad (9)$$

$$N_{pt} \approx 1.444 \times 10^{18} BV_{pt}^{-1.333} \quad cm^{-3}, \quad (10)$$

$$W_{pt} \approx 2.309 \times 10^{14} N_{pt}^{-0.8826} \quad \mu m. \quad (11)$$

In Fig. 5, the circles are for the NPT structure, whereas the dots are for the cases of the presented optimum $R_{on,pt}$ design for the PT structure, where both N_{pt} and W_{pt} are smaller than those of NPT cases. The stars are the results in Ref. [9]. Figure 6 shows the relations of the concentration N_{pt} and the width W_{pt} versus BV_{pt} when the breakdown voltage is varied from 400 to 1600 V. In Ref. [9], these relations are $W_{pt} \approx 2.086 \times 10^{-2} BV_{pt}^{7/6}$ μm, $N_{pt} \approx 1.873 \times 10^{18} BV_{pt}^{-4/3}$ cm^{-3} and $W_{pt} \approx 2 \times 10^{14} N_{pt}^{-7/8}$ μm, which are also compared in Fig. 6. The optimal concentration obtained in Ref. [9] by the Fulop model is larger, and the optimal width is smaller than those by the Chynoweth model, respectively, which will make for a large error in calculation of $R_{on,pt}$.

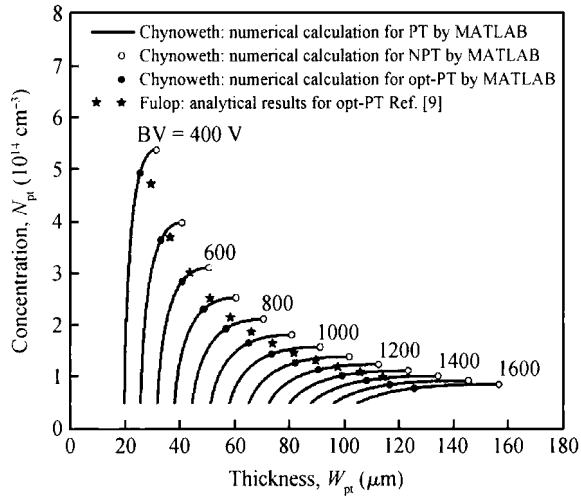

Fig. 5. The comparison of the relations of N_{pt} versus W_{pt} for the PT structure.

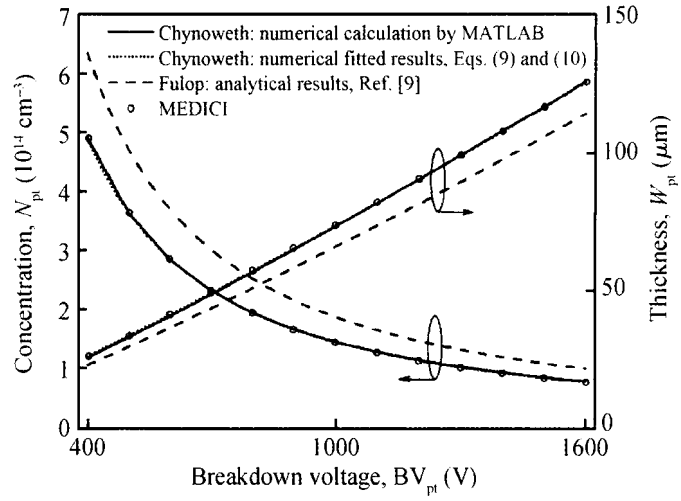

Fig. 6. The comparison of the relations of N_{pp} and W_{pp} versus BV_{pp} for the optimized PT structure.

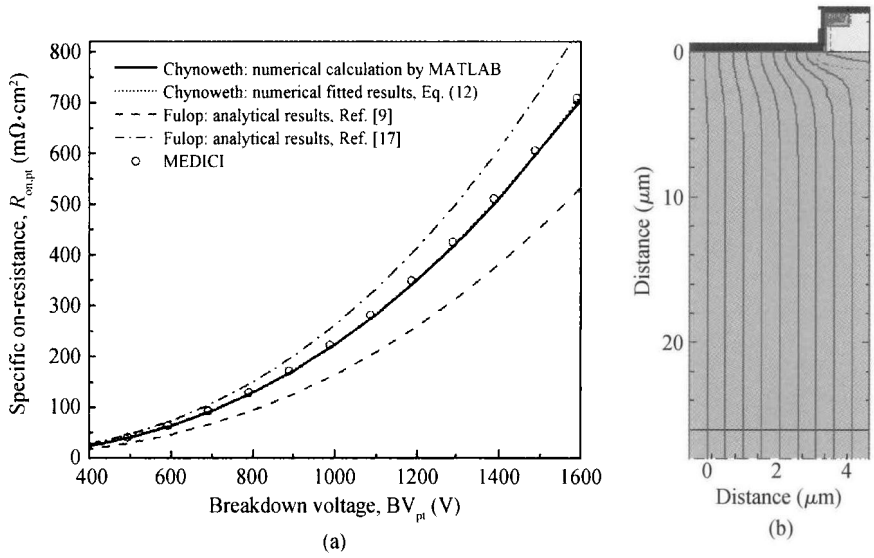

Fig. 7. The comparison of the design expressions by Chynoweth and Fulop models. (a) The comparison of relations of $R_{on,pt}$ versus BV_{pt} for the optimized PT structure. (b) The simulated 400-V trench PT VDMOSFET.

When the breakdown voltage is varied from 400 to 1600 V, the widths and concentrations for the optimum PT cases are from 81.0168% to 80.2416% and from 91.4341% to 91.6941% of those of the NPT cases, respectively, which are more accurate than the results with fixed values of 81.2% for the widths and 93.2% for the concentrations by using the Fulop model in Ref. [9].

The specific on-resistance of the optimized PT structure versus breakdown voltage can be obtained and numerically fitted by

$$R_{on,pt} \approx 9.863 \times 10^{-6} BV_{pt}^{2.453} \quad m\Omega \cdot cm^2. \qquad (12)$$

The numerical results obtained in MATLAB as well as the approximation expression in Eq. (12) are shown in Fig. 7(a). The previous results, which are established as $R_{on,pt} \approx 5.2 \times 10^{-6} BV_{pp}^{2.5}$ mΩ·cm^2 in Ref. [9] and $R_{on,pt} \approx 8.3 \times 10^{-6} BV_{pt}^{2.5}$ mΩ·cm^2 in Ref. [17], respectively, are also compared in this figure. It is seen from the figure that the results in Ref. [9] are smaller, whereas the results in Ref. [17] are bigger compared with the results in Eq. (12). Figure 7(a) also shows the simulation results from MEDICI. The simulated 400-V trench PT VDMOSFET is shown in Fig. 7(b). The other parts except for the drift region, the bias condition and the simulation models are the same as those in NPT cases, and for a required breakdown voltage, the width and doping of the drift region are given by Eqs. (9) and (10), respectively. The simulation results also show good agreement with the results from Eq. (12), verifying the accuracy of the proposed optimization method for the abrupt PT structures.

5. Conclusion

For device simulations by MEDICI, the integral of impact ionization is calculated according to the Chynoweth model-which is more accurate to depict the real devices. The design of the parameters for the NPT and PT abrupt parallel-plane p–n junctions by this model is proposed and compared with the conventional results by the Fulop model. The proposed new

expressions both for the NPT and PT cases can be used in the design of the breakdown voltage for different structures more accurately, including the cell or the termination design of some power devices.

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