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Equivalent Doping Transformation Method for Predicting Breakdown Voltage and Peak Field at Breakdown of Epitaxial-Diffused Punch-Through Junction*

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Abstract: Based on a new semi-empirical analytical method, namely equivalent doping transformation, the breakdown voltage and the peak field of the epitaxial-diffused punch-through junction have been obtained. The basic principle of this method is introduced and a set of breakdown voltage and peak field plots are provided for the optimum design of the low-voltage power devices. It shows that the analytical results coincide with the previous numerical simulation well.

Key words: epitaxial-diffused punch-through junction; breakdown voltage; peak field; equivalent doping transformation

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1 Introduction

Vertical Epitaxial-Diffused Punch-Through (EDPT) junction structure has been widely applied in various devices, such as diode, bipolar junction transistor, DMOS, IGBT and IGCT[1—4]. Compared with the non-punch-through junction, as long as a device is built on an epitaxial layer, which is thin enough, the punch-through junction is very useful in reducing the forward resistance, power loss and the switch speed.

Various first-order equations and design figures are available for 1-D calculation of the breakdown voltage under a punch-through condition[5—7]. with detailed analyses having been given by He Jin *et al*[8—9]. However, no analytical methods at present are suitable for the EDPT junction, because though generally, the doping-dependent critical field at breakdown is used[10], all the contribution to the breakdown voltage has been neglected. The numerical analysis proves that due to the strong dependence of the breakdown voltage of EDPT junction on the junction depth and the surface concentration, the diffused side contribution to the breakdown voltage can not be neglected[10, 11]. So far, little effect has been made on numerical analysis, nor has any analytical method been proposed to characterize the breakdown voltage and the peak electrical filed at breakdown of this EDPT junction.

The purpose of this paper is to propose an

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analytical method to predict the breakdown voltage and the peak field of the EDPT junction to optimize the device design, based on the equivalent doping transformation presented by He Jin *et al*[12—14]. The breakdown voltage and the peak field are expressed as a function of the substrate doping, the junction depth and the surface concentration. The analytical results are in excellent agreement with the previous simulation, showing the validity of the equivalent doping profile method, which has been used in the design of breakdown voltage for the epitaxial-diffused punch-through junction structures.

2 Equivalent Doping Profile Transformation of EDPT Junction

The cross-section view of the diffused epitaxial punch-through p^+n^-n junction is shown in Fig. 1, which is formed from a Gaussian distribution applied on the uniformly doping epitaxial layer. The substrate-to-epitaxial-transition profile is assumed to be an abrupt form that is a proper approximation of the practical process. The characterization of the epitaxial-diffused junction doping profile using the parameters of N_p, N_s, x_j, t_{epi}, is also defined in Fig. 1.

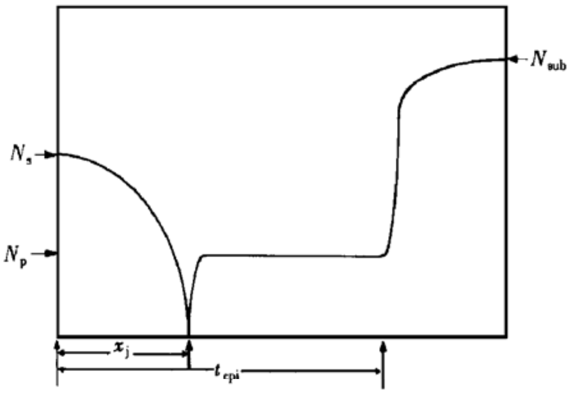

FIG. 1 Schematic of Epitaxial-Diffused Punch-Through Junction

For the sake of simplicity, the contribution of the substrate side to the breakdown voltage is neglected; the voltage can sustain the diffused side and the punch-through epitaxial layer. From Gaussion function, the diffused side doping-gradient is easily obtained as[15]

$$G_d\big|_{x_j} = \frac{2N_s}{x_j} \times \frac{\ln(N_s/N_p)}{N_s/N_p} \quad (1)$$

Similar to the equivalent doping transformation methods in References[12—14], the uniform profile of the punch-through layer approximates to the equivalent single-sided linearly graded junction with an effective gradient constant G_{eq}. In another word, the uniform doping profile of the epitaxial layer is represented by a linear doping profile. The breakdown voltage of the epitaxial-diffused punch-through junction can be obtained by using the theory of the asymmetric linearly graded junction[12], which can be re-written as

$$BV = 5.284 \times 10^9 G_{eff}^{-2/5} \quad (2)$$

where

$$\frac{1}{\sqrt{G_{eff}}} = \frac{1}{\sqrt{G_d}} + \frac{1}{\sqrt{G_{eq}}} \quad (3)$$

However, G_{eq} is un-known at present.

In order to calculate G_{eq}, three conditions are assumed to keep the electrical characteristics during the transformation constant[13].

(1) Total net charge in the space charge region at breakdown is a constant.

(2) Breakdown voltage at breakdown is a constant.

(3) The epitaxial punch-through junction and the effective single-sided linearly graded junction are both in an avalanche breakdown case.

From condition (1), the following equation is deduced:

$$E_{peak} = \frac{qN_pW_p}{2\epsilon} + \frac{BV_{PT}}{W_p} = \frac{qG_{eq}W_{eq}^2}{2\epsilon} \quad (4)$$

where BV_{PT} and $W_p = t_{Si} - x_j$ are the breakdown voltage and the depletion width of the punch-through junction, respectively.

While condition (2) leads to:

$$BV_{PT} = \frac{qG_{eq}W_{eq}^3}{3\epsilon} \quad (5)$$

It is easy to calculate the G_{eq} by solving equations (4) and (5), providing W_{eq} is known. In addition, according to the condition (3), the depletion width of the single-sided linearly graded approximation at breakdown, which is as a function of the doping gradient, is well known as[12]

$$W_{eq} = 4.8 \times 10^5 G_{eq}^{-7/15} \quad (6)$$

Substitute equation (6) into equations (4)—(5), we will finally get G_{eq}.

3 Results and Discussion

Based on the above derivations, the breakdown voltage of EDPT junction could be analytically obtained through eqs. (1), (2), (3) and G_{eq}, which gives the epitaxial layer doping concentration and thickness. According to a complete set of computations for the junction of this kind, the breakdown voltage and the maximum electric field at breakdown, being a function of the junction depth and the surface concentration, are illustrated in Fig. 2 and Fig. 3.

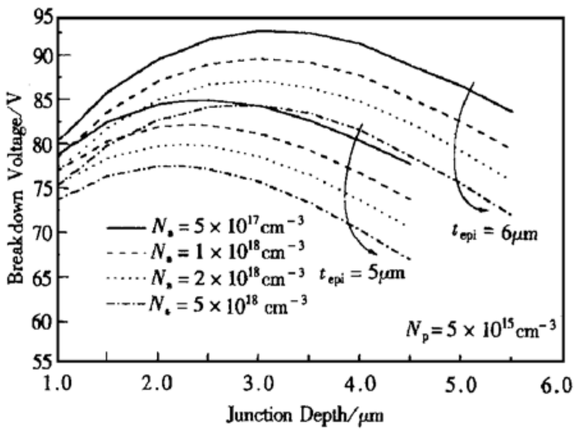

FIG. 2 Breakdown Voltage Versus Junction Depth

Not only the breakdown voltage is observed to vary significantly according to the junction depth and the surface doping concentration, but also the peak electrical field at breakdown. When the junction depth increases, the diffused-side effect on the breakdown voltage and the peak electrical field becomes evident. Therefore, the common calculation methods are not accurate due to the neglected diffused-side contribution to the breakdown voltage.

It is very interesting that the breakdown voltage of the diffused epitaxial punch-through junction has a maximum value and there are some variations in the junction depth, which are caused by two competitive effects: (1) decrease in the voltage sustaining capability of the punch-through layer owing to the thinning of the available width; and (2) increase in the similar capability of the diffused side owing to the lowering of the doping gradient there. Both effects are simultaneously brought by increasing the junction depth at a constant surface concentration. Same mechanism is responsible for the minimum value of the electric field. It should be pointed out that there are two extreme points at one identical junction depth location.

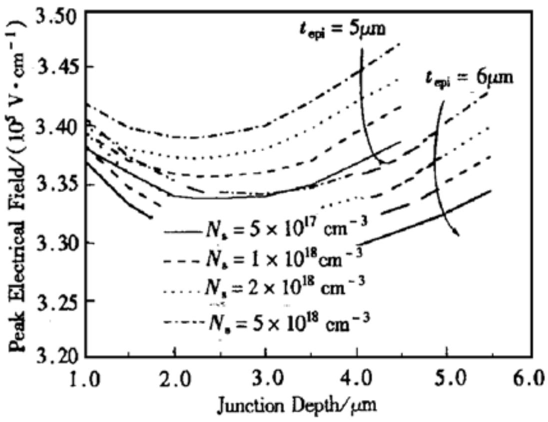

FIG. 3 Peak Field at Breakdown Versus Junction Depth

To design low voltage power devices, it is important to obtain the maximum breakdown voltage for the epitaxial layer with given thickness. Therefore, a predicted result in this analytical method is very useful for the designers to obtain an optimum junction depth, at which the maximum breakdown voltage or/and the minimum electrical field are observed.

The comparison between the analytical breakdown voltage and the numerical simulation[10] is shown in Fig. 4. As we expected, the results coincide not only in the magnitude of the breakdown voltage within a wide range of interest junction depth, but also in the peak value's location.

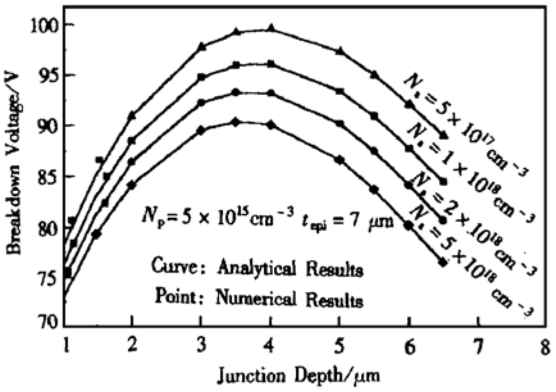

FIG. 4 Analytical and Numerical Results for Breakdown Voltage Versus Junction Depth

Besides, the comparison between the analytical peak electrical field and the previous numerical analysis[10] is also listed in Table 1. The analytical results are in good agreement with the numerical ones with the error less than 5%. This is a great improvement in the conventional first-order approximation.

Table 1 Analytical and Numerical Results for Peak Electrical Field Versus Junction Depth at Breakdown ($N_P=5\times10^{15}$cm^{-3}, $N_s=5\times10^{17}$cm^{-3}, $t_{epi}=7\mu$m)

Junction Depth/μm		1	3.5	6
Peak Field	Analytical	3.39	3.2526	3.292
/(V · cm^{-1})	Numerical	3.40	3.26	3.30

4 Conclusion

In this paper, based on the equivalent doping transformation method, the breakdown voltage and the peak electrical field of the epitaxial-diffused punch-through junction have been obtained. The analytical method correctly predicts the magnitude of the maximum breakdown voltage, peak electrical field and the location of the junction depth, at which both extreme values appear. A set of breakdown voltage and peak electrical field plots are in excellent agreement with the previous numerical simulation data.

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等价掺杂转换理论预示扩散-外延穿通 P-N 结的击穿电压和击穿峰值电场强度*

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摘要: 基于等价掺杂转换理论的应用, 得到了解析计算扩散-外延穿通 P-N 结击穿电压和击穿峰值电场强度的一系列结果. 介绍了等价掺杂转换方法的基本理论, 然后运用该理论得到了用于低压功率器件优化设计的系列击穿电压和击穿峰值电场强度计算公式, 并正确地预示了最大击穿电压和击穿峰值电场强度的位置. 理论结果显示出与以前的数值分析结果很好的一致性.

关键词: 扩散-外延穿通 P-N 结; 击穿电压; 击穿峰值电场强度; 等价掺杂转换方法

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何 进 男, 博士后, 研究方向为深亚微米器件、功率器件和器件表征.

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