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Prediction of Breakdown Voltage of Asymmetric Linearly-Graded Junction by Equivalent Doping Profile Transformation Method

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Abstract: This report describes an equivalent doping profile transformation method with which the avalanche breakdown voltage of the asymmetric linearly graded junction was analytically predicted. The maximum breakdown voltage and the different depletion layer extension on the diffused side and substrate side are demonstrated in the report. The report shows the equivalent doping profile method is valid to predict the breakdown voltage of the complex P-N junction. The analytical results agree with the experimental breakdown voltage in comparison with the abrupt junction and symmetric linearly graded junction approximations.

Key words: P-N junction; asymmetric linearly graded junction; breakdown voltage; depletion layer extension; equivalent doping profile transformation

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1 Introduction

The doping profile of the single-diffused P-N junction being a complex Gaussian or a Complementary-error function, it is impossible to obtain a closed analytical solution to the breakdown voltage[1]. In addition to full numerical techniques, analytical methods, such as the single-sided abrupt junction and the symmetric linearly-graded junction approximations, are also widely used to calculate the avalanche breakdown voltage of P-N junctions.

However, the P-N junction, formed by the diffusion of impurity into a bulk semiconductor through a window in an insulating film, often consists of a uniform substrate part and a diffused part. Allowing for the asymmetry of the space charge distribution, its behavior cannot be explained by analogy with that of the abrupt or symmetric linearly-graded junction[2,3]. In fact, a diffused junction breakdown voltage is a trade-off between the two cases above mentioned[4], whose behavior is like the composite junction with a linear gradient on one side and a constant concentration on the other side[5,6]. Nevertheless, it is still a complicated numerical method of giving the breakdown voltage of a composite junction.

The asymmetric linearly graded junction is a suitable approximation to the composite junction, whose breakdown voltage can be calculated based on the theoretical result derived by He *et al*[7]. However, it is difficult to determine the equivalent doping gradient constant on the substrate side. This report proposes a simple and useful equivalent doping profile transformation method to calculate the effective doping gradient constant on the substrate as well as the breakdown voltage of the

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asymmetric linearly graded junction. The method is a modified equivalent-doping concept proposed by He Jin *et al*[8~10]. We demonstrate that the transformation equivalent profile gradient together with the asymmetric linearly graded breakdown voltage formula can significantly simplify the breakdown voltage calculation. In addition, the various breakdown voltages are calculated based on different linear gradient constant and background doping concentration levels combination. Moreover, the characteristics of expansion of the depletion layers have been revealed.

2 Theoretical analysis

A composite P^+-N junction is shown in Fig 1. The junction has a linear gradient constant G_d on the diffusion side and a constant substrate doping

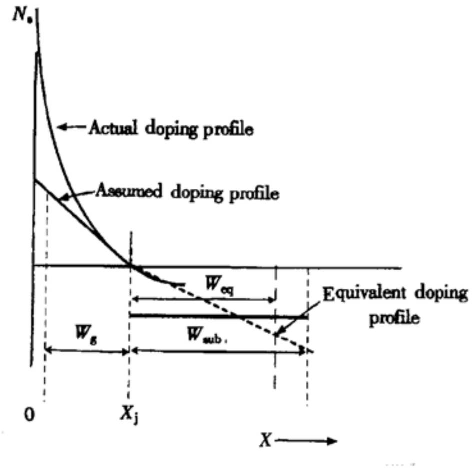

Fig. 1 Impurity distribution of the single-diffused junction and various approximation

concentration N_{sub} on the substrate side. W_g and W_{sub} are the maximum depletion width of the diffusion side and the substrate side at breakdown, respectively. Similar to the equivalent doping transformation methods[8~10], the abrupt doping profile on the substrate side is calculated approximately using one transformed single side linearly graded profile with the equivalent doping gradient constant G_{eq} and the maximum depletion layer width W_{eq} at breakdown. Literatures[8, 9] refer to the basic principle and physics meaning of this method.

The breakdown voltage of such a double-sided asymmetrical linearly graded P-N junction is given as[7]

$$V_b = 5.28 \times 10^9 G_{LR}^{-2/5} \quad (1)$$

with

$$\frac{1}{\sqrt{G_{LR}}} = \frac{1}{\sqrt{G_d}} + \frac{1}{\sqrt{G_{eq}}} \quad (2)$$

where G_d is the gradient on the diffused side.

In order to calculate G_{eq}, three conditions are set to keep the breakdown voltage constant[8~10]:

(1) Total space charges in the right space charge region at breakdown are constant.

(2) Breakdown voltage at breakdown is constant.

(3) Both the original and the transformed junctions are in the avalanche state.

Condition (1) leads to the following equation:

$$qN_{sub}W_{sub} = \frac{qG_{eq}W_{eq}^2}{2} \quad (3)$$

condition (2) leads to:

$$\frac{qN_{sub}W_{sub}^2}{2\epsilon} = \frac{qG_{eq}W_{eq}^3}{3\epsilon} \quad (4)$$

Thus G_{eq} can be easily calculated by solving equations (3) and (4), providing W_{eq} is known.

However, according to condition (3), the depletion width of the single side linearly graded junction at breakdown is known as a function of the doping gradient[7]:

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

Solving the eqs. (3) and (4) for G_{eq}, and using equation (5), we get

$$G_{eq} = 1.36 \times 10^{-10} N_{sub}^{15/8} \quad (6)$$

It is only the G_{eq} that can approximately calculate the substrate side effect on the breakdown voltage of the composite junction.

3 Results and discussion

Based on the above derivations, the diffused junction breakdown voltage can be analytically obtained using eqs. (1), (2) and (6). From a set of computations performed for composite junction in the range of practical interest, the main results were condensed in Fig. 2.

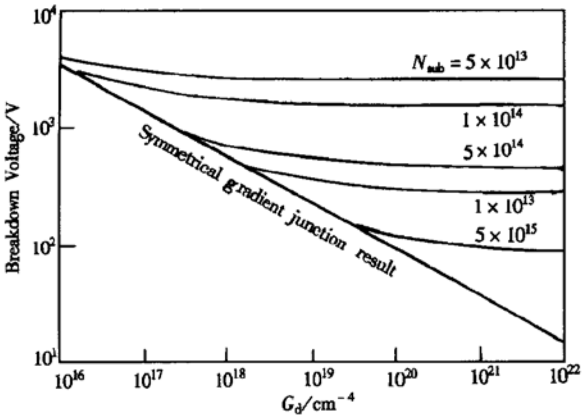

Fig. 2 Analytical calculation results of the breakdown voltage of asymmetric linearly graded junction for different combination of a diffused side gradient constant and substrate doping concentration

The behavior of the composite junction can be observed. Decreasing the substrate side concentration N_{sub} from 10^{15}cm^{-3} to 10^{13}cm^{-3}, the breakdown voltage of the composite junction departs markedly from the linearly graded case (shown by the lowest lines in Fig. 2) and tends to the value of an abrupt junction case dictated by the composite junction. If the gradient $G_d = 5\times10^{19}$cm^{-4}, this departure occurs when $N_{sub} = 10^{15}$cm^{-3}. When $G_d = 5\times10^{17}$cm^{-4} for the typical power devices[1~6], the "threshold" substrate concentration is 5×10^{14}cm^{-3}. When $N_{sub} = 5\times10^{13}$cm^{-3}, no linearly graded approximation is suitable for any practical gradient constant.

For the combination of the substrate concentration and the diffused side gradient constant, shown as the left dash line in Fig. 2, the equivalent doping transformation predicts a lower breakdown voltage in comparison with the linearly graded junction. This does not apply to the practical diffused junction though it is true in the physical principle. In this case, the symmetric linearly graded junction is suitable for the breakdown voltage calculation. Mostly, the breakdown voltage of the asymmetric linearly graded junction given by the equivalent doping profile transformation is more accurate than that given by the symmetric linearly graded junction or an abrupt junction.

In addition, the depletion width W_{sub} on the substrate side can be calculated through equation (3) or (4) using the breakdown voltage obtained. For the sake of comparison, the exact depletion width of the diffused side at breakdown as a function of the grade constant G_d is also considered. The result is shown in Fig. 3.

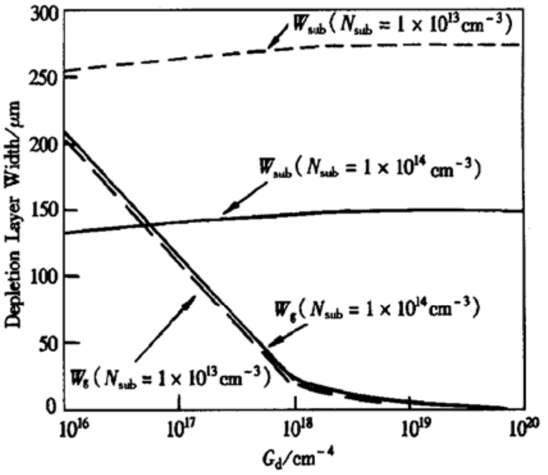

Fig. 3 Depletion layer widths at breakdown on the diffused side and substrate side for the composite junction

In Fig. 3, the depletion expansion on the diffused side can be found significantly increased and surpassing the expansion on the substrate side with the decrease of the gradient constant. At a higher substrate concentration, i. e., $N_{sub} = 10^{13}$cm^{-3}, the depletion width on the substrate is always larger than that on the diffused side, though the latter rises quickly with the decrease of the gradient constant. However, it is not true at an intermediate substrate concentration, such as when $N_{sub} = 10^{14}$ cm^{-3}. It is very strange that the depletion width of the substrate side at breakdown slightly decreases with decrease of the gradient constant. It can be concluded that the breakdown voltage is supported on both sides of the composite junction, thereby considerable expansion of the depletion width appearing on the diffused side.

From equation (1), in contrast with the abrupt or linearly graded junction, the breakdown voltage is derived, which has taken the effect of the substrate and diffused sides into account and is proved close to the experimental value of the practical junction structure. For example, for a typical power device, when $N_{sub} = 10^{14} cm^{-3}$ and the gradient constant in the practical ranges between $10^{19} \sim 10^{17} cm^{-4}$, the value of the breakdown voltage, computed via equation (1), is 1738~ 2247V, i. e., close to the experimental values recorded in the diffusion junction[11~12]. At the same gradient constant, the classic linearly graded junction seriously underestimates the breakdown voltage values: $V_b = 1475V$ when $G_d = 10^{17} cm^{-4}$ and $V_b = 230V$ when $G_d = 10^{19} cm^{-4}$. Meanwhile, at the same substrate concentration, the abrupt junction approximation also underestimates the breakdown voltage (1668V) in the same way. Similar conclusions are valid for other combination of the gradient constant and substrate concentration.

4 Conclusion

In this paper, the breakdown voltage of the asymmetric linearly graded junction was obtained analytically by the equivalent doping profile transformation. We examine the effect of the diffused side gradient constant and substrate doping concentration on the breakdown voltage and depletion widths. The analytical result accords with the experimental value compared to the abrupt junction or linearly graded junction approximations, demonstrating the validity of the equivalent doping transformation method in predicting the breakdown characteristics of a general P-N junction.

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由等价掺杂转换理论得到非对称线性缓变 P-N 结的击穿特性

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摘要: 基于等价掺杂转换理论的应用, 得到了解析计算非对称线性缓变 P-N 结击穿特性. 由于非对称线性缓变 P-N 结是单扩散 P-N 结的一个恰当近似, 因而, 研究其击穿特性可以更好地理解和设计功率器件 P-N 结的终端结构. 运用等价掺杂转换方法的基本理论得到了不同扩散掺杂梯度和衬底浓度组合系列的击穿电压. 研究了最大耗尽层宽度在扩散侧和衬底侧的扩展, 给出了它们随扩散掺杂梯度和衬底浓度组合的变化而出现的不同特点. 本方法预言的最大击穿电压较之单纯的突变结和对称线性缓变 P-N 结更接近文献报道的结果, 显示了等价掺杂转换理论的理论计算非对称线性缓变 P-N 结击穿电压的有效性.

关键词: 非对称线性缓变 P-N 结; 击穿电压; 等价掺杂转换理论

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