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Closed Analytical Solution of Breakdown Voltage for Planar Junction and Lateral Curvature Effect*

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Abstract The effect of the lateral curvature upon the breakdown voltage for a planar junction is investigated in this paper. Based on the approximation of the effective junction curvature which is determined by the junction depth and the lateral curvature, the analytical solution of breakdown voltage for the planar junction can be found, and the results agree with the numerical simulated and experimental results very well.

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1 Introduction

It is well known that the breakdown voltage for a planar junction depends on the radii of the edge and of the corners to a great extent. Baliga and Ghandhi have established an analytical solution of the breakdown voltage for cylindrical or spherical abrupt junctions, i.e. an approximation of the curved portions of the planar junction[1~5]. Their results approach to the values derived from computer by Sze and Gibbons[2]. However, the experimental results[3,4,6] demonstrate that the above solutions are not fit for all the actual situations, such as the breakdown voltage for the curved junction is higher than one for the spherical junction but lower than for the cylindrical junction when the junction is under the patterning mask. Basavanagoud *et al.*[3] drew a conclusion that this phenomena for the curved junction was caused by the effects of lateral curvature radius on the breakdown voltage. Kim *et al.*[7] also derived a 3-D analytical expression of the breakdown voltage for the planar junction. The above results could be achieved either through the numerical simulation or by the complicated inserting methods. Obviously, a more complete analysis on

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the breakdown voltage should take not only the effect of the cylindrical and/or spherical curvature into consideration but also of the lateral radius. By such 3-D numerical analysis solution, an ideal expression of breakdown voltage for a planar junction could be given accurately.

In the literature[8], the difference existing in breakdown voltages of the main junction and of the Floating Field limited Ring (FFR) is explained as the effect of the lateral curvature on the junction curvature. In this paper, we introduce the concept of the effective junction curvature in order to explain the effect of the lateral curvature on the breakdown voltage. In fact, either the side diffusion or the curvature of the lateral radius could cause the concentration of the field distribution at the junction edge. The curvature radius at the junction edge is the sum of the junction depth and the curvature radius of the lateral window[9]. Therefore, the effective junction curvature at the edge is determined by both junction depth and lateral radius, and it is affected by the cylindrical and spherical curvature. As a result, the junction is spherical in shape if the lateral radius is extremely small. On the contrary, it is cylindrical at the edge if the lateral radius is very large. In fact, comparing with the depletion width of device at a high bias voltage, the lateral radius is usually limited within a finite value, so the planar junction often includes a quasi-spherical edge. Now based on the approximation of the effective junction curvature radius, we can obtain a closed analytical solution of the breakdown voltage for the planar junction, which agrees with the numerical simulation and the experiments very well.

2 Theory

In Fig. 1, we can see a circular geometry junction, where R_m (in cm) is the radius of the window through which a p^+-diffusion have done. This parameter is named lateral curvature radius. r_d (in cm) is the curvature radius of the external boundary of a depletion-layer. The obvious xx'-axis symmetry in structure indicates that the electrical field $E(r)$ in the depletion layer is radial and practically is independent on the angular positions around the junction. It is in complete agreement with the approximations of the filed distribution at the cylindrical and spherical junctions[1,2].

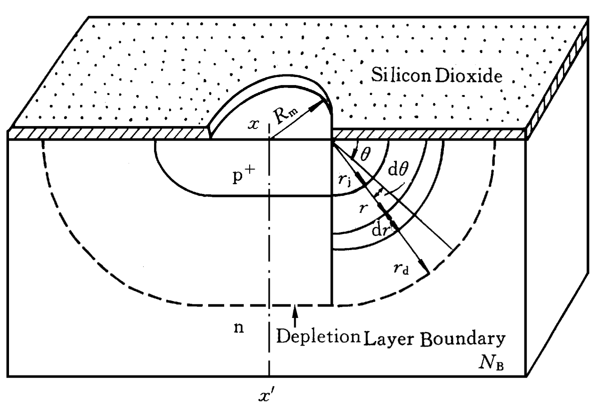

FIG. 1 Structure of an abrupt planar p^+-n junction

Gauss' law, which applies to the curved portion of an abrupt planar p^+-n junction, can be written as the equation (1) with the background doping concentration N_B[3]

$$- E(r)\int_{\theta=0}^{\frac{\pi}{2}} 2\pi(R_m + r\cos\theta)\, r\,d\theta = \left(\frac{qN_B}{\epsilon\epsilon_0}\right)\int^{r_d}\int_{\theta=0}^{\frac{\pi}{2}} 2\pi(R_m + r\cos\theta)\, r\,d\theta\,dr \tag{1}$$

Integrating and rearranging the relational expression, the electrical field can be expressed as the following equation when $r \gg r_j$

$$E(r, R_m) = -\frac{qN_B}{2\epsilon\epsilon_0} \times \frac{\frac{2}{3}(r_d^3 + r^3) + \frac{\pi}{2}R_m(r_d^2 - r^2)}{r\left(r + \frac{\pi}{2}R_m\right)} \tag{2}$$

The maximum of the electrical field at the metallurgical interface can be calculated through equation (3) as followed

$$E_m(r_j, R_m) = -\frac{qN_B}{3\epsilon\epsilon_0} \times \frac{\frac{2}{3}(r_d^3 + r_j^3) + \frac{\pi}{2}R_m(r_d^3 - r_j^3)}{r_j\left(r_j + \frac{\pi}{2}R_m\right)} \tag{3}$$

The expression (2) and (3) are the universal formulations of the electrical field at the curved portion of depletion layer for an abrupt planar junction. In fact, when $R_m = 0$ or $R_m \to \infty$, Eq. (2) and (3) can be abbreviated into the expressions for the spherical and cylindrical field respectively, which have been reported in literature[1]. Thus, by introducing the lateral curvature radius R_m, two different effects by cylindrical and spherical curvatures can be unified into one equation (2) or (3).

In order to obtain a closed analytical solution, it is necessary to simplify both Eq. (2) and Eq. (3) first. Considering the effects of the lateral radius R_m of window curvature and the expression (3) for the maximum of the electrical field, a simple expression of electrical field can be obtained. Definitions are stipulated as following

$$\eta_m = R_m / W_c \qquad \eta_j = r_j / W_c \tag{4}$$

$$r_d = W_c + r_j \tag{5}$$

where W_c is the width of the depletion layer of an ideal parallel-plane junction with a doping concentration N_B; R_m is the lateral curvature radius. Generally speaking, the width of depletion layer of actual planar junction, in many cases, is less than W_c. However, Eq. (5) is also an expression in the first-order approximations.

Consequently, Eq. (3) can be conveniently rewritten as

$$E_m(r_j, c) = -\frac{qN_B}{3\epsilon\epsilon_0}\frac{r_d^3}{(cr_j)^2} \tag{6}$$

where

$$C = \sqrt{\frac{1 + \frac{\eta_m}{\eta_j}}{1 + \left(\frac{\eta_j}{1 + \eta_j}\right)^3 + \frac{3\pi\eta_m}{4(1 + \eta_j)} - \frac{3\pi\eta_m\eta_j^2}{4(1 + \eta_j)(1 + \eta_j)^2}}} \tag{7}$$

In order to verify the above analysis, when R_m / r_j is 5, we compare the normalized maximum electrical fields derived from Eq. (6) with one from Eq. (3) (see Fig. 2). Figure 2 shows that when R_m / r_j is equal to 5, the results derived from simplified expression agree quite well with the ones from the exact equation. The same is true for all the value of R_m ranging from 0.01 to 1000.

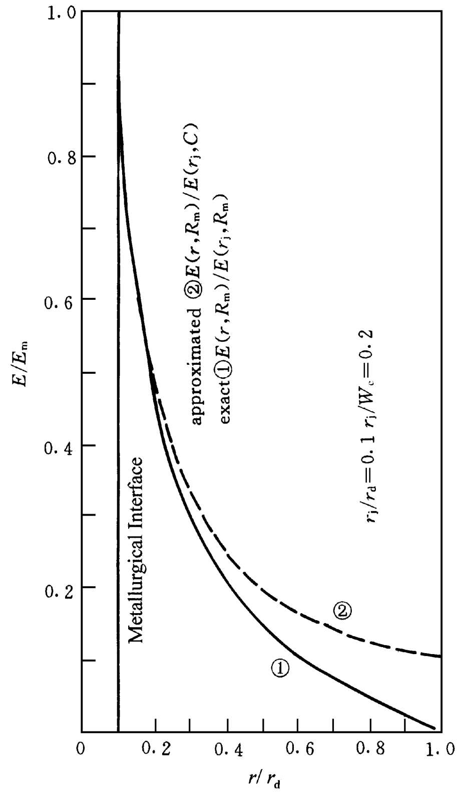

FIG. 2 Normalized maximum electrical field from the exact Eq. (3), being a very close approximation to those from Eq. (6) in each position

We stipulate the effective curvature radius of the planar junction as below

$$r_{jeff} = C r_j \tag{8}$$

After substituting some parameters in Eq. (6) by our definition, the maximum field can be expressed as Eq. (9)

$$E_m(r_{jeff}) = -\frac{qN_B}{3\epsilon\epsilon_0} \times \frac{r_d^3}{r_{jeff}^2} \tag{9}$$

It is very interesting that the Eq. (9) is just the expression of the spherical junction proposed by Baliga[10]. In the case of a spherical junction, in order to obtain the breakdown voltage for a planar junction, it is necessary to get the ionization integration by calculating the electrical field distribution through Eq. (2). Based on the fact that the impact ionization occurs primarily at a high electrical field and close to the metallurgical interface, a closed solution can be obtained by means of the approximation of the electric field distribution from Eq. (10)

$$E(r_{eff}) = k/r_{eff}^2 \tag{10}$$

With Fulop's formula for the ionization integral equation, we can get an expression for the critical electrical field at breakdown by integrating from r_{jeff} to infinity

$$E_c(r_{jeff}) = \left(\frac{13}{A\, r_{jeff}}\right)^{1/7} \tag{11}$$

where $A = 1.8\times10^{-35}$.

The E_c which is normalized to the parallel plane case, can be obtained by the following equation:

$$\frac{E_c(r_{jeff})}{E_{cpp}} = \left(\frac{13}{8}\frac{W_c}{r_{jeff}}\right)^{1/7} = \left(\frac{13}{8\eta_{jeff}}\right)^{1/7} \tag{12}$$

where $\eta_{jeff} = r_{jeff}/W_c$.

It proves that an universal expression of the critical field for the planar junction has nothing to do with the specific R_m and r_j. With the critical field at breakdown, an expression for the breakdown voltage can be derived. It also can be normalized to the breakdown voltage of a parallel-plane case as followed

$$\frac{BV(r_{jeff})}{BV_{cpp}} = \eta_{jeff} + 2.14\eta_{jeff}^{6/7} - (\eta_{jeff}^{3} + \eta_{jeff}^{13/7})^{2/3} \tag{13}$$

According to the expression of the BV_{cpp}, the breakdown voltage, $BV(r_j, C)$ for the planar junction can also be rewritten as

$$BV(r_j, C) = 5.34 \times 10^{13} N_B^{-3/4}\{(Cr_j/W_c)^2 + 2.14(Cr_j/W_c)^{6/7} - [(Cr_j/W_c)^3 + (Cr_j/W_c)^{13/7}]^{2/3}\} \tag{14}$$

Equations (13) and (14) can be abbreviated to a sphere junction case when R_m is zero and to a cylindrical junction case when R_m goes to infinity.

3 Discussion

To get a breakdown voltage for the planar junction, R_m and r_j must be normalized to the W_c. The published result and our analytical solution of the normalized breakdown voltages are described as a function of η_m and η_j in Fig. 3. The lateral curvature R_m affects the value of the breakdown voltage greatly. It limits the breakdown voltage for the planar junction within a range of special values which are lower than one of the cylindrical junction but higher than of the sphere junction.

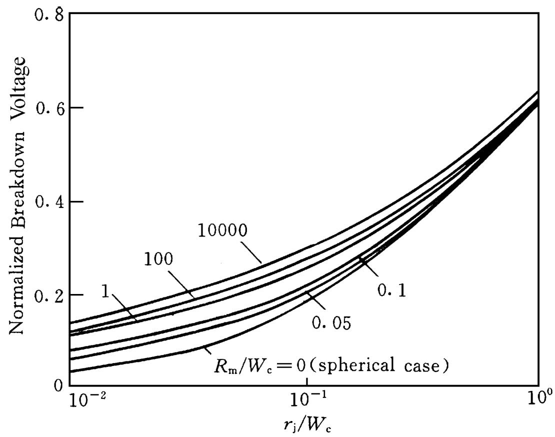

FIG. 3 Normalized breakdown voltage for the planar junction as a function of the lateral radius of window curvature

Table 1 is the comparison of the breakdown voltages obtained from (A) experiment, (B) numerical result and (C) analytical solution described in this paper respectively.

(Note: $N_B = 1.3 \times 10^{13} cm^{-3}$, $BV_{CPP} = 7800V$, and $W_c = 895\mu m$)

Table 1 Comparison of experimental, numerical results and analytical solution

$r_j/\mu m$	$R_m/\mu m$	Breakdown voltage /V		
		Experiment[4]	Theory	
			Numerical[7]	Analytical
12	130	722	718	796
26	75	1015	988	981
26	200	1200	1146	1131

The results of the analytical model are in a complete agreement with the literature[4].

Comparing these results from the experiments of Yabuta *et al.* [7], the breakdown voltages in the analytical expression acts as a function of the lateral radius of window curva-

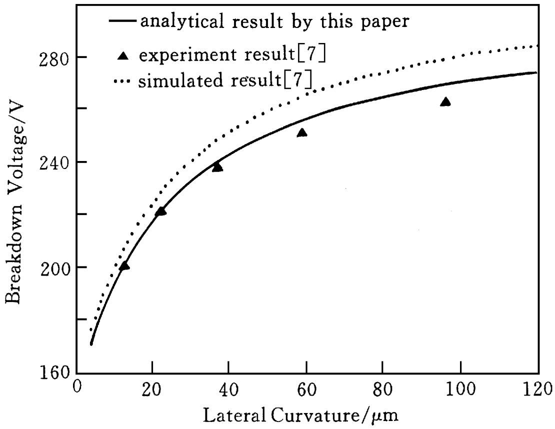

FIG. 4 The comparison of the breakdown voltages obtained by the analytical expression with the results of experiments and quasi-3D device simulation[7]

ture R_m (see Fig. 4). The background doping and the junction depth are 1.4 $\times 10^{14} cm^{-3}$ and 5μm respectively, and R_m varies from 5μm to 100μm. In Fig. 4, the breakdown voltage decreases significantly as R_m lessening due to the effect of window curvature. The breakdown voltages derived from the analytical solution are rather close to the experimental results. Therefore, the analytical solution we discussed above can be used to solve the 3-D problem about the planar junction.

4 Conclusions

In this article, we analyze and discuss the effect of lateral radius of window curvature on the breakdown voltage for an planar junction. Based on the simplification of the 3-D electrical field distribution and the definition of the effective junction curvature, a closed analytical solution of planar junction can be obtained which is affected by the lateral curvature on the breakdown. All analytical results are in agreement with the experimental and simulative data which have been reported in the literatures. Therefore, this method can be used to analyze the breakdown phenomena of planar junction when the junction termination design has to be taken into consideration.

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