A New Quasi 2-Dimensional Analytical Approach to Predicting Ring Junction Voltage, Edge Peak Fields and Optimal Spacing of Planar Junction with Single Floating Field Limiting Ring Structure

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Abstract: A new quasi 2-dimensional analytical approach to predicting the ring voltage, edge peak fields and optimal spacing of the planar junction with a single floating field limiting ring structure has been proposed, based on the cylindrical symmetric solution and the critical field concept. The effects of the spacing and reverse voltage on the ring junction voltage and edge peak field profiles have been analyzed. The optimal spacing and the maximum breakdown voltage of the structure have also been obtained. The analytical results are in excellent agreement with that obtained from the 2-D device simulator, MEDICI and the reported result, which proves the presented model valid.

Key words: floating field limiting ring; breakdown voltage; edge peak electric filed; ring spacing

EEACC: 2560B; 2560R

CLC number: TN386 **Document code**: A **Article ID**: 0253-4177(2001)06-0700-06

1 Introduction

The enhancement in the electric field at the edges and corners of curved portion of the planar junction severely lowers the breakdown voltage of the practical devices. In order to overcome this drawback and get a higher breakdown voltage, various junction termination techniques (JTTs) have been developed. Among them, floating field limiting ring method (FFLR)[1—2] makes it possible to obtain a high breakdown voltage with relatively shallow junction, so it applies to the high voltage and high-speed semiconductor switching devices.

Many numerical techniques have been described in the past years to analyze the breakdown voltage and the optimum spacing of FFLR system, which give some valuable information on the optimization of spacing and prediction of breakdown characteristics[3—7]. The numerical technique is time-saving in calculation, with the results corresponding with the specific case of the junction depth and the background doping level. For multiple FFLR structure, the problem becomes more evident. On the other hand, most of the previous analytical works have been severely restricted to the 1-D case[8—12], which can hardly meet the practical design of the junction termination due to the 2-dimensional (2-D) characteristics of electric field distribution. In order to predict the correct optimal spacing and the improved breakdown voltage of the FFLR structure, the 2-D voltage and the edge peak field profiles are necessary. However, no detailed report has been found on the FFLR structure, owing to its complication.

In this paper, a simple but accurate quasi 2-D analytical approach is proposed to analyze the

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Received 20 November 2000, revised manuscript received 4 January 2001

FFLR structure, based on the cylindrical symmetric solution and the critical field concept. The analytical expressions of the ring voltage as well as the edge peak field profiles and optimal spacing are also proposed. This approach applies to the analytical estimation of ring voltage and edge peak field profiles over a wide range of parameters, such as the junction depth, spacing and anode voltage. In addition, the optimal spacing and the maximum breakdown voltage can be predicted, too. The analytical results have been verified by the 2-D device simulator, MEDICI[13].

2 Quasi 2-D Analytical Approach

The cross-section of a p$^+$-n planar junction with a single FFLR structure is shown in Fig. 1, where the main and ring junctions in the non-punch-through case are assumed to be abrupt and cylindrical with the same radius of curvature. Assuming the reverse voltage is applied to the cathode N$^+$ region and the anode P$^+$ region is grounded.

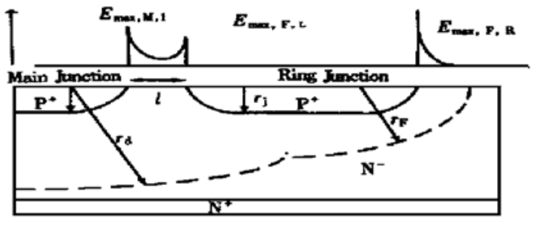

FIG. 1 Cross-Section of Planar Junction with FFLR and Diagram of Edge Peak Electric Field

Generally, the cylindrical portion of an abrupt planar junction for the quasi 2-D electric field should satisfy the Poisson's equation of the cylindrical coordinate.

$$\frac{1}{r}\times\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}V}{\mathrm{d}r}\right)=-\frac{1}{r}\times\frac{\mathrm{d}}{\mathrm{d}r}(rE)=-\frac{qN_\mathrm{d}}{\epsilon\epsilon_0}\qquad r_\mathrm{j}\leqslant r\leqslant r_\mathrm{d}\tag{1}$$

where N_d is the background doping concentration, r_j is the junction depth, ϵ is the relative permission, ϵ_0 and q are the free space dielectric constant and electron charge, respectively.

Solving the electric field and voltage distribution at the boundary conditions that the electrostatic potential of the anode and the electric field of the outer boundary of the junction are both zero, we obtain

$$E=\frac{qN_\mathrm{d}}{2\epsilon\epsilon_0}\left(\frac{r_\mathrm{d}^2-r^2}{r}\right)\tag{2}$$

and

$$V=\frac{qN_\mathrm{d}}{2\epsilon\epsilon_0}\left(\frac{r_\mathrm{j}^2-r^2}{2}+r_\mathrm{d}^2\ln\left(\frac{r}{r_\mathrm{j}}\right)\right)\tag{3}$$

If the FFLR is absent at first, a reverse biased voltage V_R will be applied. Then, the outer boundary of the depletion region of the main junction, r_d, can obtained from (4) and the maximum field at the main junction edge be obtained from (5).

$$V_\mathrm{R}=\frac{qN_\mathrm{d}}{2\epsilon\epsilon_0}\left(\frac{r_\mathrm{j}^2-r_\mathrm{d}^2}{2}+r_\mathrm{d}^2\ln\left(\frac{r_\mathrm{d}}{r_\mathrm{j}}\right)\right)\tag{4}$$

$$E_{\max,M,0}=\frac{qN_\mathrm{d}}{2\epsilon\epsilon_0}\left(\frac{r_\mathrm{d}^2-r_\mathrm{j}^2}{r_\mathrm{j}}\right)\tag{5}$$

Now, the ring junction is placed with a spacing l from the main junction. Based on the semiconductor device physics, the ring junction voltage V_F, which is generally defined as the electrostatic potential difference between the cathode and ring junction, must satisfy the following conditions

$$V_\mathrm{F}=\begin{cases}V_\mathrm{R} & l=0,\\ 0 & l+r_\mathrm{j}\geqslant r_\mathrm{d},\\ x & 0<x<V_\mathrm{R}, r_\mathrm{j}<l+r_\mathrm{j}<r_\mathrm{d}\end{cases}\tag{6}$$

It is evident that the spacing satisfies the third term in (6) so that FFLR plays an important role in the voltage distribution over the field profiles, i.e. the FFLR operates in the punch-through mode. Thus, $(r_\mathrm{j}+l)$ is less than r_d.

Consequently, the main junction voltage V_M, usually defined as the electrostatic potential difference between the ring and the main junctions, is determined by the distance from the main junction, r_j, to the ring junction, $r_\mathrm{j}+l$. In fact, V_M is the electrostatic potential of the ring junction when the anode electrostatic potential is zero. It is well known that the presence of FFLR does not perturb the depletion extension from the main junction. Therefore, V_M can be obtained from (7) based on (3)

$$V_M = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_j^2}{2} + r_d^2\ln\left[\frac{r_j + l}{r_j}\right] - \frac{(r_j + l)^2}{2}\right] \quad (7)$$

Since the main ring junctions support the total reverse voltage simultaneously, the ring junction voltage V_F is V_R minus V_M, as shown in (8)

$$V_F = V_R - V_M \quad (8)$$

Combining (4), (7) and (8), the simple expression of V_F can be written as:

$$V_F = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{(r_j + l)^2}{2} + r_d^2\ln\left[\frac{r_d}{r_j + l}\right] - \frac{r_d^2}{2}\right] \quad (9)$$

As for the ring junction, whose voltage and field profiles also satisfy the equations of (2) and (3), (8) can be further written as:

$$V_F = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{(r_j + l)^2}{2} + r_d^2\ln\left[\frac{r_d}{r_j + l}\right] - \frac{r_d^2}{2}\right]$$

$$= \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_j^2 - r_F^2}{2} + r_F^2\ln\left[\frac{r_F}{r_j}\right]\right] \quad (10)$$

$$E_F = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - r^2}{r}\right] \quad (11)$$

Solving the combined equations (9) and (10), the outer boundary of the ring junction, r_F, can be obtained and the maximum field on the right of the ring junction can be expressed as

$$E_{max,F,R} = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - r_j^2}{r_j}\right] \quad (12)$$

According to the FFLR principle[9], the electric field of the main junction is reduced due to the transfer of the shared voltage from the main junction to the ring one. Therefore, the edge maximum field intensity $E_{max,M,1}$ of the main junction is determined by the maximum field difference caused by the cathode voltage and the ring junction voltage at the main junction edge.

$$E_{max,MF} = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - (r_j + l)^2}{r_j + l}\right] \quad (13)$$

Then, $E_{max,M,1}$ can be given below

$$E_{max,M,1} = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_d^2 - r_j^2}{r_j}\right] - \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - (r_j + l)^2}{r_j + l}\right] \quad (14)$$

Similarly, the maximum field on the left of the ring junction can be expressed as

$$E_{max,FP,L} = \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - r_j}{r_j}\right] - \frac{qN_d}{2\epsilon\epsilon_0}\left[\frac{r_F^2 - (r_j + l)^2}{r_j + l}\right] \quad (15)$$

3 Ring Voltage and Edge Peak Electric Field Profiles

With a given reverse bias voltage and some structure parameters such as junction depth and doping concentration, the main junction and ring junction voltage can be easily calculated from equations (4), (7) and (9). In order to verify the analytical results, the 2-D semiconductor device simulator, MEDICI, is used to analyze the same structure. The surface doping concentration of the anode P^+ region is $1\times10^{20}\,cm^{-3}$ with a Gaussian profile. The analytical results and the numerical ones are in excellent agreement with each other, as is shown in Fig. 2 and Fig. 3.

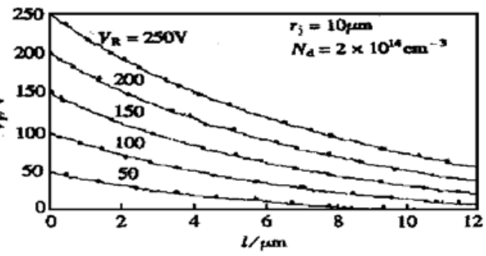

FIG. 2 Ring Junction Voltage Versus Spacing Under Different Reverse Voltages

From Fig. 2, it is seen that the ring junction voltage decreases with the increase of the spacing, thus, the function relationship is very complex. In the first order approximation, the linear relation between the ring junction voltage and the spacing is valid within the definite range of the spacing[8,10].

The dependence of the ring junction voltage on the reverse voltage is shown in Fig. 3. Obviously, the relationship between V_R and V_F is linear, which has been proved experimentally and theoretically in the literatures[2,8]. However, the slope between V_R and V_F decreases with the increase of spacing, as is different from the previous 1-D analysis and the Temple′ experimental results[1,2].

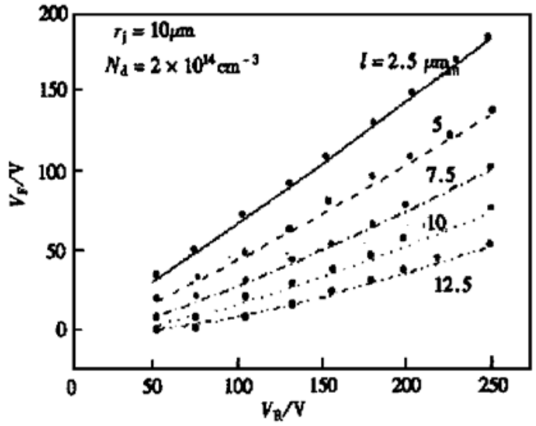

FIG. 3 Ring Junction Voltage Versus Reverse Voltage with Different Spacings

Figure 4 shows the effect of the spacing on the edge field of the main junction and ring junction. With the increase of spacing, the peak field of the main junction edge increases, while the ring junction's field decreases, as is similar to the experimental curve reported by Seui Yasuda *et al*.[4]. It should be pointed out that there exists an optimal spacing at the place where the edge fields of the main and ring junction are equal and of a minimum electric field. The optimal spacing is observed to increase with the reverse voltage increasing.

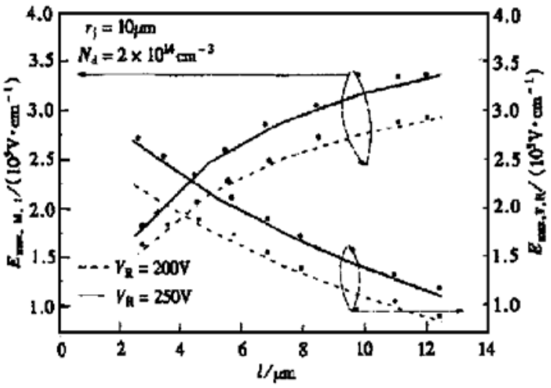

FIG. 4 Edge Maximum Electric Fields Versus Spacing Under Different Reverse Voltages

In most studies of FFLR structure, the peak electric field of the left edge of the ring junction is neglected due to the small value. However, the real amplitude is still unknown up to date. Based on the analytical model presented, Figure 5 shows the variation of the left edge peak field with the increase of the spacing. The left edge peak filed of the ring junction is 4—5 times less than the right edge one. It is surprising that there appears a peak in the left edge peak field with the increase of spacing, which has been verified by result obtained from MEDICI simulator[13].

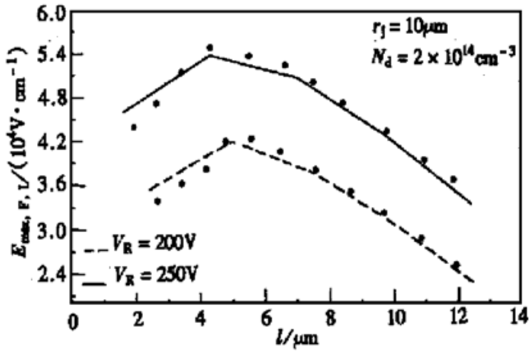

FIG. 5 Left Edge Electric Field of Ring Junction Versus Spacing Under Different Reverse Voltage

4 Optimization of Spacing and The Maximum Breakdown Voltage

In a FFLR structure, an optimal spacing exists when an avalanche breakdown occurs simultaneously at both the junctions. And the breakdown voltage reaches the maximum. If the spacing is either too small or too large, a high field will occur at the main ring junction edge and a lower breakdown voltage take place. It is difficult to obtain the optimal spacing because it is concerned with many parameters, such as the junction depth, lateral radius, doping concentration, the width of the ring junction and reversed voltage. However, owing to the critical field for the curved junction, it is possible to analytically obtain the optimal spacing of the FFLR and the maximum breakdown voltage. At different optimal condition of the FFLR structure, there is always an optimal spacing of FFLR when the edges of the main and ring junction simultaneously equal to the critical intensity E_{CC}, and the breakdown voltage approaches the maximum value.

The critical field at breakdown for a planar junction, with the cylindrical curved edge obtained from equation (1)[11], is integrated from r_j to infinity

$$E_{CC}=\left[\frac{6}{Ar_j}\right]^{1/7} \tag{16}$$

where $A=1.8\times10^{-35}\mathrm{cm}^{-1}$.

With this expression, the optimization of spacing and the maximum breakdown voltage are described as follows: (1) by combining (12) and (16), the maximum depletion outer boundary $r_{f,max}$ of the ring junction at breakdown is obtained; (2) $r_{f,max}$ is substituted into (10) to calculate the ring junction voltage BV_F; (3) Let the maximum field at the edge of the main junction be the critical field; by solving the combined equations of (9), (10) and (14), the optimal spacing and outer boundary of the main junction depletion region, $r_{d,M,max}$ at breakdown are further calculated. The formulae for the optimal spacing and $r_{d,M,max}$ can be simplified as

$$BV_{FFR}=\frac{qN_d}{2\epsilon\epsilon_0}\left\{\frac{(r_j+l_{opt})^2}{2}+\left[\frac{2\epsilon\epsilon_0E_{CC}r_j}{qN_d}+r_j^2+\frac{r_{F,max}^2-(r_j+l_{opt})^2}{r_j+l_{opt}}r_j\right]\right.$$
$$\left.\times\ln\left[\frac{\left[\frac{2\epsilon\epsilon_0E_{CC}r_j}{qN_d}+r_j^2+\frac{r_{F,max}^2-(r_j+l_{opt})^2}{r_j+l_{opt}}r_j\right]^{1/2}}{r_j+l_{opt}}\right]-\frac{\epsilon\epsilon_0E_{CC}r_j}{qN_d}-\frac{r_j^2}{2}-\frac{r_{F,max}^2-(r_j+l_{opt})^2}{r_j+l_{opt}}\times\frac{r_j}{2}\right\} \tag{17}$$

$$r_{d,opt}=\left\{\frac{2\epsilon\epsilon_0E_{CC}r_j}{qN_d}+r_j^2+\left[\frac{r_{F,max}^2-(r_j+l_{opt})^2}{r_j+l_{opt}}\right]r_j\right\}^{\frac{1}{2}} \tag{18}$$

(4) Substitution of $r_{d,M,max}$ for (7) can obtain the main junction breakdown voltage BV_m; (5) Finally, the maximum breakdown voltage BV_{FFLR} of the FFLR structure is the sum of BV_m and BV_F.

Figure 5 shows the variation in the breakdown voltage of a single ring structure as a function of the ring spacing when $r_j=10\mu m$, $N_d=2\times10^{14}\mathrm{cm}^{-3}$, $W_{cpp}=81.1\mu m$ and $BV_{pp}=1000V$, where W_{cpp} and BV_{pp} are the maximum depletion layer width at breakdown and the breakdown voltage of the parallel-plane junction with the doping substrate concentration N_d of $2\times10^{14}\mathrm{cm}^{-3}$, respectively. It is obtained that $l_{opt}=7\mu m$ and $BV_{FFLR}=621V$, which are in good agreement with the results when $\eta=r_j/W_{cpp}=10/81.1=0.13$ and $BV_{FFLR}/BV_{pp}=621/1000=0.62$ that are obtained from the Temple′ normalized breakdown voltage versus normalized curvature curve[2].

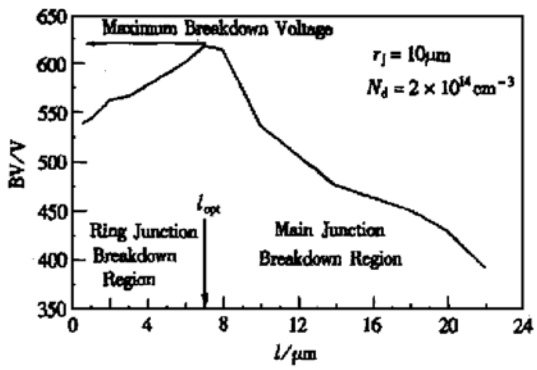

FIG. 6 Breakdown Voltage of FFLR Versus Spacing Between Main Junction and Ring Junction

5 Conclusion

A quasi 2-D analytical model has been proposed for the voltage and edge peak field profiles of the planar junction with a single floating field li-miting ring. The effects on the voltage and edge electric field profiles of the spacing and reverse voltage have been analyzed, and the results are in a good agreement with the results from the 2-D device simulator, MEDICI. With the critical field concept, some expressions have also been deduced to predict the optimal spacing and the maximum breakdown voltage, which have proved accurate by comparing the numerical analysis with the previous experimental result. This model can greatly simplify the optimum design of the FFLR structure.

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新的二维解析方法预言场限环结构的电压分布和边界峰值电场及环间距的优化

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摘要: 提出了一个新的二维解析方法预言场限环结构的电压分布和边界峰值电场及环间距优化. 采用与平面结物理机理最接近的圆柱坐标对称解进行分析, 给出了场限环结构极为简单的各电压和边界峰值电场表达式. 讨论了不同环间距和反偏电压对场限环电压的影响, 并用流行的 2-D 半导体器件模拟工具 MEDICI 对解析计算进行了验证. 根据临界电场击穿近似, 讨论了环间距的优化设计并给出了优化环间距表达式. 在一定结深和掺杂浓度时, 理论计算给出了与数值分析一致的优化环间距和最高击穿电压值.

关键词: 场限环; 击穿电压; 峰值电场; 环间距

EEACC: 2560B; 2560R

中图分类号: TN386 **文献标识码**: A **文章编号**: 0253-4177(2001)06-0700-06

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2000-11-20 收到, 2001-01-04 定稿