Numerical Analysis of Single Photon Avalanche Photodiodes With Improved Structure

W. J. Wang*, L. Lin, T. X. Li, N. Li, W. D. Hu, W. Lu, X. S. Chen
National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yu Tian Road, Shanghai, 200083, China
wangwj@mail.sitp.ac.cn

***Abstract*-In this paper, the effects of the thickness of the multiplication region (Tm), the sheet charge density of the charge control layer (Dc)and the guard ring design to a separate absorption, grading, charge, and multiplication InGaAs/InP single photon avalanche diode (SPAD)'s performance are numerically discussed. Optimized Tm and Dc are designed for a SPAD. Implanted guard ring is revealed to be easier and better to suppress the junction edge electric field compared with the floating guard ring.**

I. INTRODUCTION

Single photon detection is becoming more and more important for quantum key distribution and advanced LADAR [1,2]. For a single photon avalanche photodiode (SPAD) operated under the Geiger mode, how to get a high detection efficiency to dark count ratio is the key parameter. Much research has been made, such as the design of the guard ring [3], the effect of the thickness of the multiplication region and the charge layer [4]. But few papers show the relationship between these factors and the effects of these factors to the performance of a SPAD. A detailed design guideline concerning the guard ring and the thickness of the key layer is significant.

In this paper, effects of the thickness of the multiplication region (Tm), the sheet charge density of the charge control layer (Dc) and the design of the guard ring to the SPAD's performance are discussed. Finally we show a design guideline for an InGaAs/InP SPAD with high detection efficiency to dark count ratio. And an InGaAs/InP SPAD with optimized structure is shown.

II. MODEL DESCRIPTION AND NUMERICAL RESULTS

To investigate the effects of Tm and Dc, a simple mesa structure model of a separate absorption, grading, charge, and multiplication (SAGCM) InGaAs/InP avalanche photodiode (APD) is designed, as shown in fig. 1. Only Tm and Dc are varied, whereas the other terms are kept constant. Numerically simulation of the device is performed using the software ISE-TCAD, with the carrier generation-recombination process accounting for Shockley-Read-Hall, trap-assisted tunneling (TAT), Auger, radiative, band-to-band tunneling (BBT) terms. The physical parameters of numerical model are seriously calibrated with the experimental results of the same structure.

A. Sheet charge density of the charge control layer

Dc ranges from 1.7 to 4.2E12 cm^{-2}. As shown in fig. 2, the difference between the breakdown voltage (V_{br}) and the punch through voltage (V_{pt}) is reduced by increasing Dc, which owes to the decreasing electric field in the absorption layer and the increasing one in the multiplication layer. This is very advantageous to reduce the tunneling dark current, get a higher avalanche gain and a sharp rising avalanche current, which is essential for single photon counting[5]. But Dc is not as more

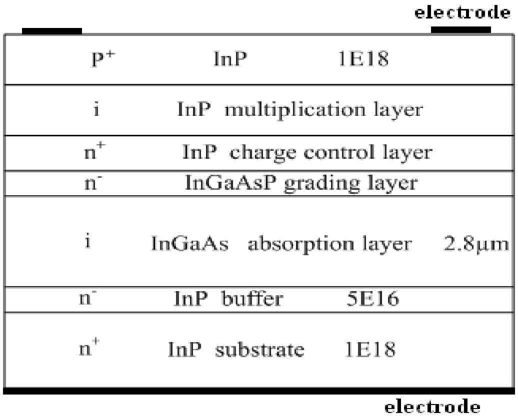

Fig. 1. Schematic cross-section of the simulated mesa APD

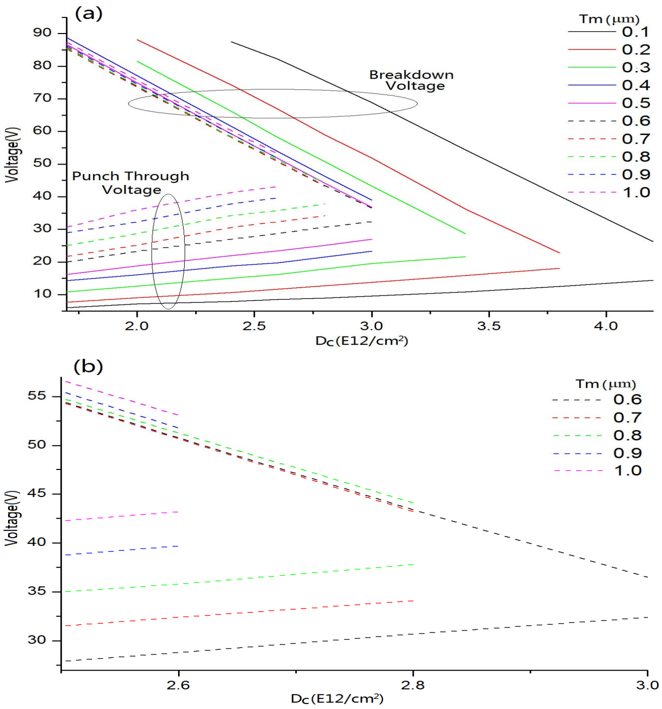

Fig. 2. V_{pt} and V_{br} versus Tm and Dc. (a) Tm changes from 0.1 to 1.0μm. (b) An enlarged view for Tm from 0.6 to 1.0μm .

978-1-4244-7017-4/10/$26.00 ©2010 IEEE

as better, there exists a maximum Dc for a fixed Tm. If Dc is too large, the breakdown would happen before the absorption layer is depleted. When Tm is increased, the maximum of Dc is reduced.

B. Thickness of the multiplication layer

Tm varies from 0.1 to 1.0 µm. As shown in fig. 2, for a fixed Dc, there is also a maximum Tm. And the larger Dc is, the smaller Tm is. To easily get an accurate Tm, which is controlled by diffusion of Zinc in a planar APD, we should choose an appropriate Dc. As seen in fig. 2, when Dc is fixed as 4.2E12 cm^{-2}, Tm larger than 0.1µm is forbidden, which is very difficult to control.

There isn’t a linear relation between Tm and the difference of V_{br} and V_{pt}. As seen in fig. 2, the minimum difference occurs when Tm is 0.6µm and Dc is the maximum 3E12 cm^{-2}. This is the optimized structure for a SPAD.

C. Structure of the guard ring

For a planar InGaAs/InP APD, Zinc diffusion is used to form p-doped InP layer in fig. 1. To suppress the edge pre-breakdown, guard ring is used. Two types of guard ring structure are designed in fig. 3 (a) (b). Optimized Tm and Dc are used. Here Tm1 for two structures are fixed as 0.6µm. Compared with structure (a), (b) is easier and better to suppress the edge electric field as shown in fig. 3 (c) (d). When doping level p1 and p2 in (b) is much lower than p^{+}, especially when p2 is also lower than p1, the electric field near the junction edge (A,B) is best suppressed.

It is aslo found that optimized Tm and Dc are beneficial to suppress the edge electric field.

III. EXPERIMENTAL RESULTS

A SAGCM InGaAs/InP SPAD was fabricated with the guard ring designed as fig. 3 (a). Dc is 3E12 cm^{-2}, and Tm is about 0.9 µm. With the optimized structure, a gain of more than 100 is achieved as shown in fig. 4 (a). Fig. 4 (b) shows the spatial distribution of the photocurrent across the detector’s surface. The photocurrent at the edge C and D (shown in fig. 3 (a)) is suppressed to be 40% of the value in the center of the photosensitive area.

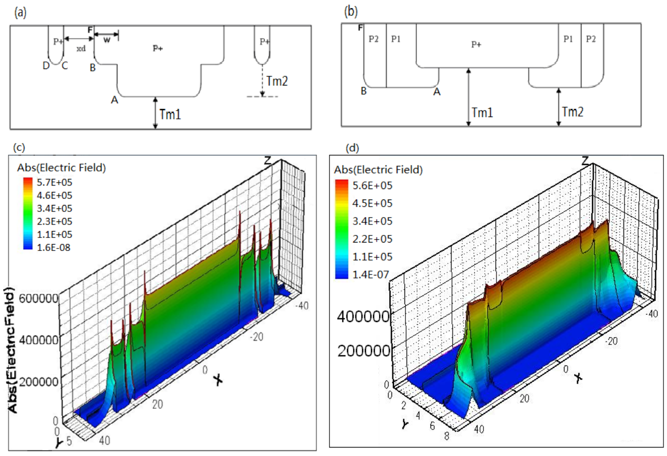

Fig. 3. (a) Diffused floating guard ring. (b) Implanted guard ring. (c) Electric field profile with guard ring(a). (d) Electric field profile with guard ring(b).

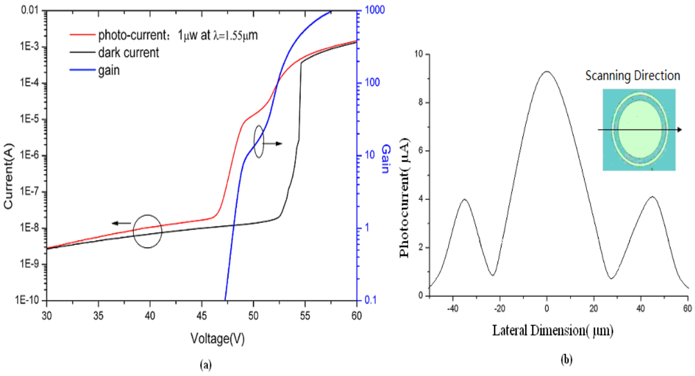

Fig. 4. (a) Current and gain versus voltage characteristics. (b) Spatial distribution of the photocurrent.

IV. CONCLUSION

In this study, effects of Dc, Tm and the guard ring to the SPAD’s performance are numerically investigated. The difference between V_{br} and V_{pt} is reduced by increasing Dc and has no linear relation with Tm. There exist optimized Tm and Dc to get a minimum difference, which is important for single photon counting. Compared with floating guard ring, implanted guard ring is easier and better to suppress the edge electric field. Finally, we get a gain of more than 100, and the edge photocurrent is suppressed to be 40% of the center.

ACKNOWLEDGMENT

This work was supported by STCSM under Contract No. 08DZ1400701, State Key Basic Research Program of China via Contract No. 2006CB921204.

REFERENCES

[1] Rengarajan Sudharsanan1, Ping Yuan, Joseph Boisvert, Paul McDonald, Takahiro Isshiki, Shoghig, Mesropian, and Ed Labios, “Single Photon Counting Geiger Mode InGaAs(P)/InP Avalanche Photodiode Arrays For 3D Imaging,” Proc. of SPIE, Vol. 6950, 69500N, 2008.

[2] Yuan, Z. L.; Dixon, A. R.; Dynes, J. F.; Sharpe, A. W.; Shields, A. J., “Gigahertz quantum key distribution with InGaAs avalanche photodiodes, ” Applied Physics Letters, v 92, n 20, p 201104,2008.

[3] Kyung-Sook hyun, Youngmi Paek, Yong-Hwan Kwon, Sungmin Hwang, Jongin Shim, Seong Joon Ahn, “Pre-breakdown suppression in planar InP/InGaAs avalanche photodiode using deep floating guard ring,” Applied Physics Letters, v 85, n 23, pp.5547-5549,2004.

[4] K. Sugihara, E. Yagyu, Y. Tokuda, “Numerical analysis of single photon detection avalanche photodiodes operated in Geiger mode,” Joural of applied physics, 99, 124502, 2006

[5] Yonglin GU, Fow-sen Choa, Yan Feng, Xiucheng Wu, Stewart Wu, Bing Guan, Peter Su,Michael A.Krainak,“ Single-photon avalanche photodiode with improved structure usingan innovative current bias scheme,”Proc. of SPIE, Vol. 6890, 68900N,2008.