Conference materials
UDC 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.143

Investigation on the effects of the multiplication area shape on the dark count rate in InGaAs/InAlAs single-photon avalanche photodiodes

V.V. Zavodilenko [1, 2, 3] ✉, A.A. Filyaev [1, 2, 3], A.V. Losev [1, 2, 4], I.D. Pavlov [1, 2]

[1] National University of Science and Technology MISIS, Moscow, Russia;
[2] "QRate" LLC, Skolkovo, Russia;
[3] HSE University, Moscow, Russia;
[4] National Research University of Electronic Technology MIET, Zelenograd, Russia
✉ v.zavodilenko@goqrate.com

Abstract. In this paper the influence of the multiplication area shape on the dark count rate (DCR) of InGaAs/InAlAs single-photon avalanche photodiodes (SPADs) is discussed. This study is carried out within the framework of SPAD design parameter optimization. The diode structure has been simulated in the T-CAD calculation environment. The structure with three levels of multiplication area with a smooth transition is the most optimal one. This structure will achieve higher quantum efficiency during the diode operation.

Keywords: multiplication area, dark count rate, single-photon avalanche photodiodes, single-photon detector

Funding: The study was commissioned by JSCo "RZD".

Citation: Zavodilenko V.V., Filyaev A.A., Losev A.V., Pavlov I.D., Investigation on the effects of the multiplication area shape on the dark count rate in InGaAs/InAlAs single-photon avalanche photodiodes, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 242–247. DOI: https://doi.org/10.18721/JPM.163.143

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/licenses/by-nc/4.0/)

Материалы конференции
УДК 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.143

Исследование влияния формы зоны умножения на уровень темнового счета в InGaAs/InAlAs однофотонных лавинных фотодиодах

В.В. Заводиленко [1, 2, 3] ✉, А.А. Филяев [1, 2, 3], А.В. Лосев [1, 2, 4], И.Д. Павлов [1, 2]

[1] Национальный исследовательский технологический университет МИСиС, Москва, Россия;
[2] ООО «КуРэйт», Сколково, Россия;
[3] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия;
[4] Национальный исследовательский университет МИЭТ, г. Зеленоград, Россия
✉ v.zavodilenko@goqrate.com

Аннотация. В данной работе рассматривается влияние формы области умножения на скорость темнового счета (DCR) InGaAs/InAlAs однофотонных лавинных фотодиодов (ОЛФД). Данное исследование проводится в рамках оптимизации параметров конструкции ОЛФД. Структура диода была смоделирована в расчетной среде T-CAD.

Ключевые слова: область умножения, скорость темнового счета, однофотонные лавинные фотодиоды, детектор одиночных фотонов

© Zavodilenko V.V., Filyaev A.A., Losev A.V., Pavlov I.D., 2023. Published by Peter the Great St. Petersburg Polytechnic University.

Финансирование: Исследовательская работа выполнена по заказу ОАО «РЖД».

Ссылка при цитировании: Заводиленко В.В., Филяев А.А., Лосев А.В., Павлов И.Д. Исследование влияния формы зоны умножения на уровень темнового счета в InGaAs/InAlAs однофотонных лавинных фотодиодах // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 242–247. DOI: https://doi.org/10.18721/JPM.163.143

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/)

Introduction

Single-photon avalanche diode (SPAD) for detecting radiation with wavelength λ = 1550 nm can be made of various materials. The development of SPADs based on materials such as Si/Ge, InGaAs/InP and InGaAs/InAlAs continues in the scientific community [1–9]. So, a promising structure such as InGaAs/InAlAs will be investigated in this work.

The advantage of the InAlAs material as a multiplication area is its high electron mobility, which allows the excited avalanche to be quenched much faster and the structure to be transferred to an equilibrium state. Thus, this device can have a higher limiting frequency and better afterpulse characteristics compared to a device with a multiplication area made of InP material. This is due to the fact that the mobility of holes in InP is lower than the mobility of electrons in InAlAs [10].

In the present work we investigated the influence of the shape of the multiplication area on the dark count rate of InGaAs/InAlAs SPADs in order to optimize its design parameters.

Materials and Methods

The modelling was carried out with the T-CAD system. In the T-CAD simulation, specific values of the carrier lifetime were set as a parameter to calculate the recombination rate according to the Schockley-Reed-Hall mechanism. Also, radiative and Auger recombination were taken into account in the calculation. In finite element modelling, a system of equations consisting of continuity equations for electrons and holes and Poisson's equation was solved.

In order to limit the active region of the multiplication region (the region where the main avalanche generation process takes place), it is necessary to use different widths of the multiplication region in the active and inactive multiplication regions. In the active region, it is necessary to achieve a higher field strength, so the width of the forbidden region should be smaller. The following problems arise when implementing this principle of building an active region.

1) It is necessary to make a transition between the two widths of the multiplication region. This can be done using either a sharp or a smooth transition. However, any sharp transition will result in a local increase in intensity and therefore a significant increase in the dark count rate when the instrument is operating in Geiger mode.

2) More than one transition can be used to minimize the field strength in the inactive region. This means that not only two different multiplication region widths can be used, but three or more. This solution makes it possible to significantly reduce the volume of high electric field areas in the inactive region and, consequently, to significantly reduce the dark count rate when the device is operated in Geiger mode.

Three SPAD structures with different multiplication area shapes were proposed (Fig. 1). The first structure with two levels of the multiplication area and a sharp transition, the second structure with three levels of the multiplication area and a sharp transition, and the third structure with three levels of the multiplication area and a smooth transition. The width of the multiplication area in the active region was the same in all structures, and was 0.8 μm.

Results and Discussion

The simulation and analysis of electric field strength profiles in different structures have shown that creation of smooth transitions at the level boundaries of the multiplication area is an extremely effective method of DCR reduction in SPAD (Fig. 2).

© Заводиленко В.В., Филяев А.А., Лосев А.В., Павлов И.Д., 2023. Издатель: Санкт-Петербургский политехнический университет Петра Великого.

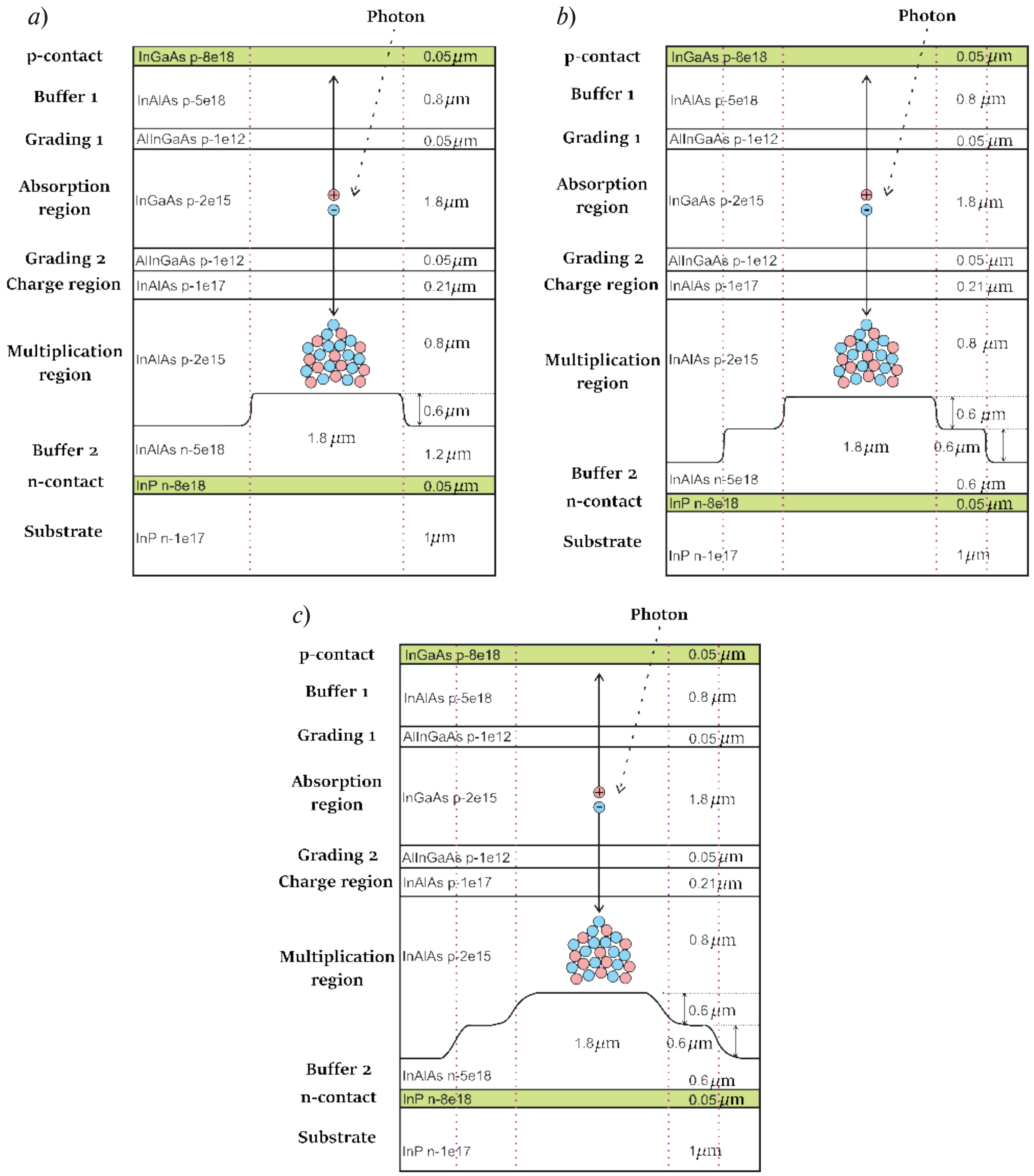

Fig. 1. Schematic representation of the simulated structures: structure with two levels of the multiplication area and a sharp transition (*a*); with three levels of the multiplication area and a sharp transition (*b*); structure with three levels of the multiplication area and a smooth transition (*c*)

A structure with two levels of multiplication region with a sharp transition is shown in Fig. 2, *a*. The disadvantage of using a sharp transition is a large local increase in the electric field strength, as shown in Fig. 2, *b*. For the section x = 10.2 μm, the electric field strength increased to values of 700 kV/cm, which is 40% stronger than the field in the remaining active region 500 kV/cm. This field increase led to an increase in the avalanche generation rate in this local area of about 60 dB. Since the size of this region is about 0.5 μm, we can estimate the contribution of this detriment to the overall DCR.

A structure with three levels of multiplication region with a sharp transition is shown in Fig. 2, *c*. The described optimization of the structure, on the contrary, has further aggravated the problem of the local increase of the electric field and the avalanche generation rate because another ring has been added (the outer one) in which we have again seen the effect of the local increase of the parameters at the sharp transition. As can be seen in Fig. 2, *d*, the electric field strength in the second ring reaches 620 kV/cm.

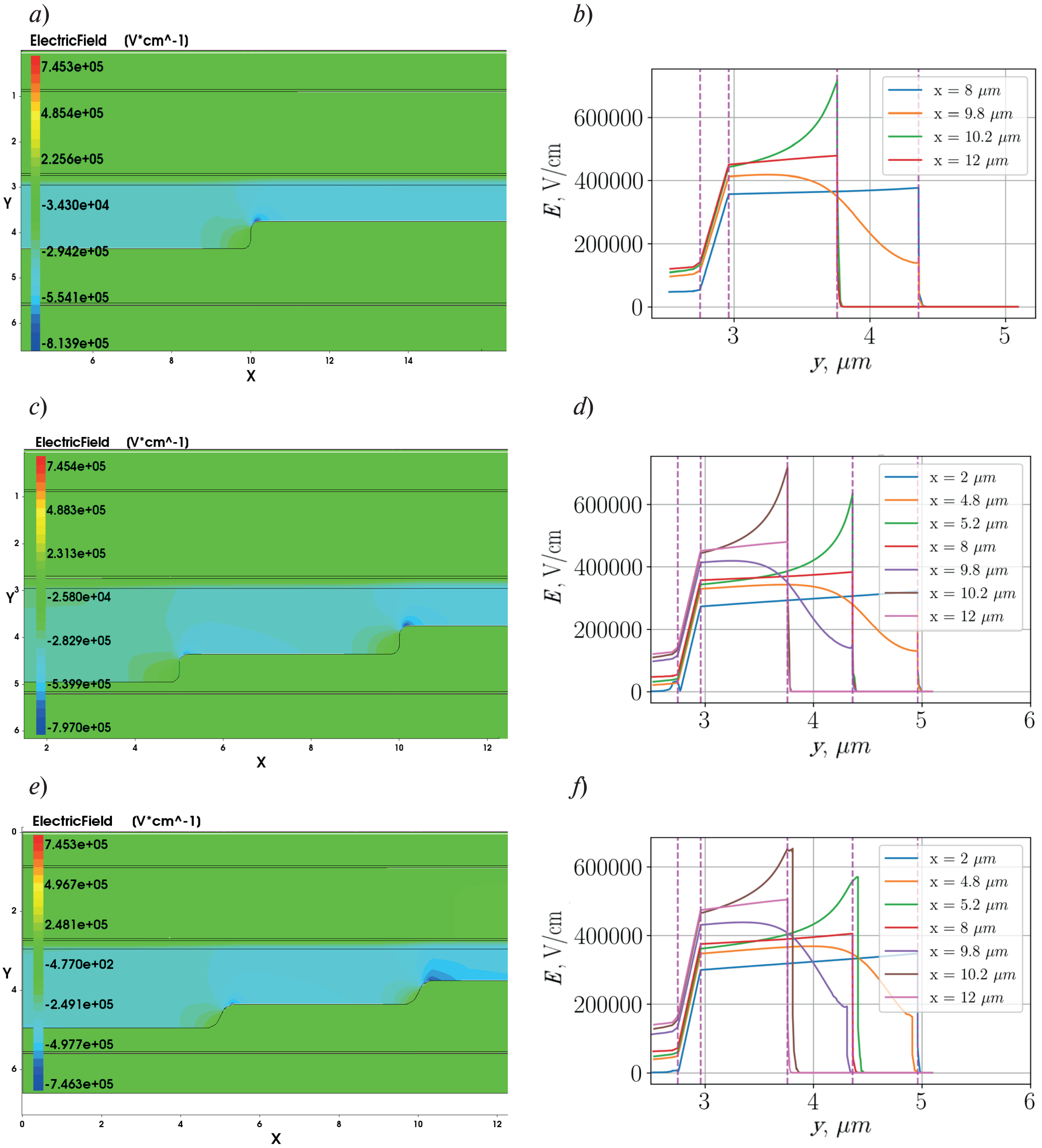

Fig. 2. A two-level structure of the multiplication region with a sharp transition: (*a*) heat map of the electric field strength distribution, (*b*) electric field distribution profile in the cross-sections indicated in figure 2 (*a*); a three-level structure of the multiplication region with sharp transition: (*c*) heat map of the electric field strength distribution, (*d*) electric field distribution profile in the cross-sections indicated in figure 2 (*c*); a three-level structure of the multiplication region with smooth transition: (*e*) heat map of the electric field strength distribution, (*f*) electric field distribution profile in the cross-sections indicated in figure 2 (*e*)

A structure with three levels of multiplication region with a smooth transition is shown in Fig. 2, *f*. Using a smooth transition has reduced the electric field strength in the region of maximum local enhancement to 620 kV/cm from 700 kV/cm with a sharp transition (Fig. 2, *f*).

It has reduced the ratio of the avalanche generation rate in the local enhancement region to that in the active region by two orders of magnitude.

If it was possible to achieve sufficiently smooth transitions (Fig. 2) in the design of the device so that the dark count rate in the local boosts was not more than 20 dB greater than in the active region of the device, a three-level multiplication area can be used.

The main advantage of three-level multiplication area structure with a smooth transition is the low local increase in electric field strength (see Fig. 2). Such effect leads to higher value of quantum efficiency of SPAD during its operation.

Conclusion

Therefore, a structure with three levels of multiplication area with a smooth transition is the most optimal. The developed SPAD structure with three levels of multiplication area and smooth transitions can also be used for avalanche photodiode devices operating in linear mode. This device has the following property: when the intensity increases by an order of magnitude, the current will similarly change by an order of magnitude, which is convenient in terms of the linearity of the characteristic. Moreover, the device has a small dark current, and therefore a low signal to noise ratio.

Acknowledgments

The study was commissioned by JSCo “RZD”.

REFERENCES

1 **Baek S.H., Yang S.C., Park C.Y., Park C.W., Cho S.B., Ryu S.W.,** Room temperature quantum key distribution characteristics of low-noise InGaAs/InP single-photon avalanche diode, Journal of the Korean Physical Society. 78 (7) (2021) 634–641.

2. **Lee Y.S., Wu P.L., Chen Y.J., Shi J.W.,** Neat temporal performance of InGaAs/InAlAs single photon avalanche diode with stepwise electric field in multiplication layers, IEEE Access. 9 (2021) 32979–32985.

3. **Kovalev V.I.,** Nature of Photoelectric Effect in a Ge-on-Si SPAD at Ultralow Energy in Incident Pulsed Laser Radiation, Optics. 2 (1) (2021) 45–53.

4. **Liang Y., Xu B., Fei Q., Wu W., Shan X., Huang K., Zeng H.,** Low-timing-jitter GHz-gated InGaAs/InP single-photon avalanche photodiode for LIDAR, IEEE Journal of Selected Topics in Quantum Electronics. 28 (2) (2021) 1–7.

5. **Liang Y., Chen Y., Huang Z., Bai G., Yu M., Zeng H.,** Room-temperature single-photon detection with 1.5-GHz gated InGaAs/InP avalanche photodiode, IEEE Photonics Technology Letters. 29 (1) (2016) 142–145.

6. **Kuzmenko K., Vines P., Halimi A., Collins R.J., Maccarone A., McCarthy A., Greener Z.M., Kirdoda J., Dumas D.C.S., Llin L.F., Mirza M.M., Millar R.W. Paul D.J., Buller G.S.,** 3D LIDAR imaging using Ge-on-Si single–photon avalanche diode detectors, Optics Express. 28 (2) (2020) 1330–1344.

7. **Tian Y., Li Q., Ding W., Wu D., Lin Z., Feng X., Zhang H., Yu X., Zhao Y.,** High speed and high sensitivity InGaAs/InAlAs single photon avalanche diodes for photon counting communication, Journal of Lightwave Technology. 40 (15) (2022) 5245–5253.

8. **Zhang J., Xu H., Zhang G., Chen Y., Wang H., Tan K.H., Wicaksono S., Sun C., Kong Q., Gong X.,** Hybrid and heterogeneous photonic integrated near-infrared InGaAs/InAlAs single-photon avalanche diode, Quantum Science and Technology. 8 (2) (2023) 025009.

9. **He T., Yang X., Tang Y., Wang R., Liu Y.,** High photon detection efficiency InGaAs/InP single photon avalanche diode at 250 K, Journal of Semiconductors. 43 (10) (2022) 102301.

10. **Chen J., Tong J., Wang S.X., Hu W.Y., Xu Q., Xie X.M., Dai Q., Shi Z., Yu L., Song H. Z.,** Study on impact ionization in charge layer and multiplication layer of InAlAs/InGaAs SAGCM avalanche photodiodes, Optoelectronic Devices and Integration VII. SPIE.10814 (2018) 289–295.

THE AUTHORS

ZAVODILENKO Vladimir V.
v.zavodilenko@goqrate.com
ORCID: 0000-0002-3252-2984

LOSEV Anton V.
a.losev@goqrate.com
ORCID: 0000-0002-6030-2532

FILYAEV Alexandr A.
a.filyaev@goqrate.com
ORCID: 0000-0001-7319-8001

PAVLOV Igor D.
ip@goqrate.com
ORCID: 0000-0001-8865-556X

Received 25.07.2023. Approved after reviewing 11.08.2023. Accepted 14.08.2023.

© Peter the Great St. Petersburg Polytechnic University, 2023