Conference materials
UDC 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.184

Investigation of the avalanche delay effect in sine-gated single-photon detector

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

[1] National University of Science and Technology MISIS, Moscow, Russia;

[2] "QRate" LLC, Skolkovo, Russia;

[3] National Research University of Electronic Technology MIET, Zelenograd, Russia;

[4] HSE University, Moscow, Russia

✉ a.losev@goqrate.com

Abstract. A sine-gated single-photon detector (SPD) intended for use in a quantum key distribution (QKD) system is considered in this paper. An "avalanche delay" effect in the sine-gated SPD is revealed. This effect consists in the appearance of an avalanche triggered at the next gate after the photon arrival gate. It has been determined experimentally that the nature of this effect is not related to the known effects of afterpulsing or charge persistence. This effect negatively affects the overall error rate in the QKD system. The influence of the main detector control parameters, such as temperature, gate amplitude and comparator's threshold voltage, on the avalanche delay effect was experimentally established.

Keywords: avalanche delay, single-photon avalanche diodes, single-photon detector

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

Citation: Losev A.V., Filyaev A.A., Zavodilenko V.V., Pavlov I.D., Investigation of the avalanche delay effect in sine-gated single-photon detector, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 459–462. DOI: https://doi.org/10.18721/JPM.163.184

Материалы конференции
УДК 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.184

Исследование эффекта задержки лавины в детекторе одиночных фотонов с синусоидальным стробированием

А.В. Лосев [1, 2, 3] ✉, А.А. Филяев [1, 2, 4], В.В. Заводиленко [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 МИЭТ, г. Зеленоград, Россия;

[4] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия

✉ a.losev@goqrate.com

Аннотация. В данной статье рассматривается детектор одиночных фотонов (ДОФ) с синусоидальным стробированием, предназначенный для использования в системе квантового распределения ключей (КРК). Обнаружен эффект «задержки лавины» в результате эксплуатации такого детектора. Этот эффект негативно влияет на общий уровень ошибок в системе КРК. Экспериментально установлено влияние основных параметров управления детектором на эффект задержки лавины.

Ключевые слова: задержка лавины, однофотонные лавинные диоды, детектор одиночных фотонов

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

Ссылка при цитировании: Лосев А.В., Филяев А.А., Заводиленко В.В., Павлов И.Д. Исследование эффекта задержки лавины в детекторе одиночных фотонов с синусоидальным стробированием // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 459–462. DOI: https://doi.org/10.18721/JPM.163.184

Introduction

A single-photon detector (SPD) is a device capable of sensing single photons at a specific wavelength. Such a device has many applications [1–6], but the most promising application is in quantum key distribution (QKD) [7]. There are several types of devices that can be used as single-photon detectors [8]. The optimum device to create a miniaturised SPD and a compact QKD system as a whole is the InGaAs/InP based single-photon avalanche diode (SPAD).

It is important to minimise the level of SPD false triggers, which entails an increased error rate for a QKD system with such a detector as part of it. One way to keep noise to a minimum is to set the control parameters of the detector correctly.

One recently discovered effect is the avalanche delay effect, which causes false triggering of a sine-gated SPD in an adjacent gate. In this paper the influence of the detector control parameters on this negative effect is established experimentally.

Materials and Methods

A special setup was used to measure the SPD parameters. It includes a synchronization system, a laser radiation source, a system of beam splitters, a system of variable optical attenuators with controlled output power, an SPD under examination, and an oscilloscope. All components of the system are controlled by software created in the LabVIEW environment.

Results and Discussion

In our experiments we observe the effect of occurrence the avalanche triggers at the next gate after the photon arrival gate. We analyze the next possible reasons of occurrence of this effect. Our custom InGaAs/InP SPAD based SPD was tested to make a decision on what’s the main reason of this shifted avalanche triggers. Let us determine experimentally whether the effects of the afterpulsing and the charge persistence effect affect the experimentally observed effect:

1) Afterpulsing effect: the initial (here we mean that this is the charge from first photon or from the low-amplitude and unregistered avalanche) charge trapped at the first gate, and release at the second gate. The approach to verify or falsify is to perform measurements with different temperatures. If histograms didn’t change its form, it means that this effect is not depend on the temperature and is not due to simple trapping.

2) Charge persistence effect: The initial charge is trapped at the potential well at the absorption/grading regions heterointerface. This effect should be strongly depended on the gate amplitude and its bias and virtually not depend on the temperature.

It was found experimentally that the nature of this effect is not related to the known effects of afterpulsing or charge persistence. As we can see on the Fig. 1, there is not temperature dependence. All three figures have very similar histogram forms and relative peaks height and positions. So, that this effect is not due to afterpulsing effect. In Fig. 2 we can see that effect of triggering photon at the next gate has more manifestation at the low gate voltages. On the contrary, charge persistence effect has more manifestations at the high gate amplitude, as we conclude in our work [9]. This means that the effect is of a fundamentally new nature.

The initial avalanche is too low, and didn’t have time to grow enough to trigger the comparator. In this case, there is a lot of free carriers at the structure, that will dissolve, and will not trigger the avalanche due to SPAD stays at the off state. But these free charges (or detrapped charges) will trigger the avalanche at the next gate. We can lower the comparator discrimination threshold V_{th} to increase the probability of comparator triggering by low amplitude avalanches. In this case we will see the lowering the second peak height.

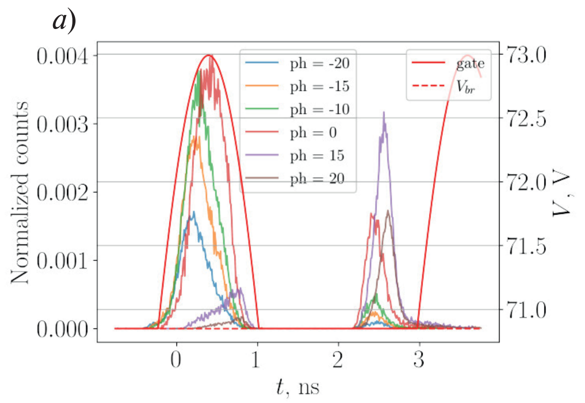

Fig. 1. Measured time resolution for SPD for different temperatures: $T = -35$ °C (*a*) and $T = -55$ °C (*b*). Gate amplitude is 3.25 V. The meaning of the phase $ph = 0$ denotes the maximum quantum efficiency. Shifted in according to *ph*. V_{br} – breakdown voltage

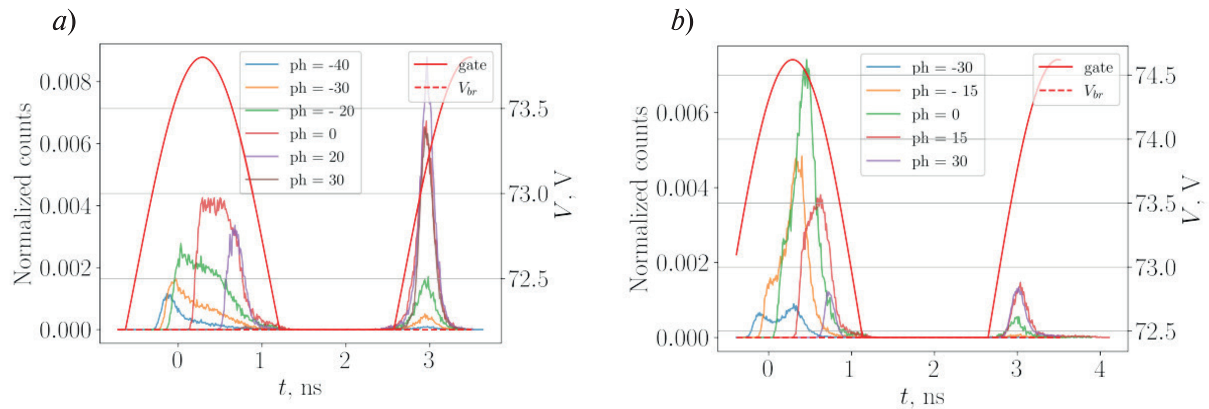

Fig. 2. Measured time resolution for SPD for different gate amplitudes: $V_g = 1.3$ V (*a*); $V_g = 2$ V (*b*). The meaning of the phase $ph = 0$ denotes the maximum quantum efficiency. Shifted in according to *ph*. V_{br} –breakdown voltage

Now we perform measurements with different comparator's threshold levels. We make measurements on the SPD with $V_g = 3.25$ V and temperature $T = -50$ °C. We tested the comparator's threshold voltage: $V_{th} = 1$ V and $V_{th} = 1.35$ V. Then more this voltage is, than more probability, that small avalanche will trigger the comparator and consequently accounted. We present these measurements results on the Fig. 3.

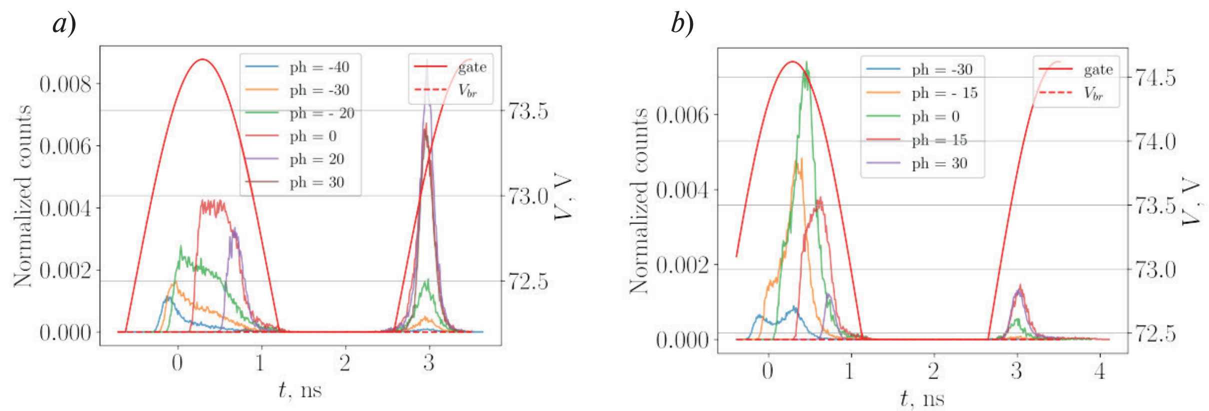

Fig. 3. Measured time resolution for SPD for different comparator's threshold voltage: $V_{th} = 1$ V (*a*); $V_{th} = 1.35$ V (*b*). The meaning of the phase $ph = 0$ denotes the maximum quantum efficiency. Shifted in according to *ph*. V_{br} –breakdown voltage

These figures show a strong dependence of the height of the second peak on the comparator threshold voltage: the height of the second peak decreases as this voltage increases.

Conclusion

We can conclude, that this effect is due to avalanche delay effect. The sense of this effect is the next: the avalanche at the end of the gate has no time to growing enough to be registered, and continue growing at the next gate, if has not been quenched by high gate voltage.

Acknowledgments

The study was commissioned by JSCo "RZD".

REFERENCES

1. **Yu C., Shangguan M., Xia H., Zhang J., Dou X., Pan J.W.,** Fully integrated free-running InGaAs/InP single-photon detector for accurate lidar applications, Optics express. 25 (13) (2017) 14611–14620.
2. **Zhang X., Shi Y., Shan Y., Sun Z., Qiao W., Zhang Y.,** Enhanced ν-optical time domain reflectometry using gigahertz sinusoidally gated InGaAs/InP single-photon avalanche detector, Optical Engineering. 55 (9) (2016) 094101.
3. **Lee C., Johnson B., Jung T., Molnar A.,** A 72×60 angle-sensitive SPAD imaging array for lens-less FLIM, Sensors. 16 (9) (2016) 1422.
4. **Kiktenko E.O., Pozhar N.O., Anufriev M.N., Trushechkin A.S., Yunusov R.R., Kurochkin Y.V., Lvovsky A.I., Fedorov A.K.,** Quantum-secured blockchain, Quantum Science and Technology. 3 (3) (2018) 035004.
5. **Al-Rawhani M.A., Hu C., Giagkoulovits C., Annese V.F., Cheah B.C., Beeley J., Velugotla S., Accarino C., Grant J. P., Mitra S., Barrett M.P., Cochran S., Cumming, D.R.,** Multimodal integrated sensor platform for rapid biomarker detection, IEEE Transactions on Biomedical Engineering. 67 (2) (2019) 614–623.
6. **Ceccarelli F., Gulinatti A., Labanca I., Rech I., Ghioni M.,** Development and characterization of an 8x8 spad-array module for gigacount per second applications, Photon Counting Applications 2017. International Society for Optics and Photonics. 10229 (2017) 102290E.
7. **Huang X.J., Lu F.Y., Wang S., Yin Z.Q., Wang Z.H., Chen W., He D.Y., Fan-Yuan G.J., Guo G.C., Han Z.F.,** Dependency model for high-performance quantum-key-distribution systems, Physical Review A. 106 (6) (2022) 062607.
8. **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.
9. **Losev A., Zavodilenko V., Koziy A., Kurochkin Y., Gorbatsevich A.,** Dependence of functional parameters of sine-gated InGaAs/InP single-photon avalanche diodes on the gating parameters, IEEE Photonics Journal. 14 (2) (2022) 1–9.

THE AUTHORS

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

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

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 26.07.2023. Accepted 28.07.2023.