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RESEARCH ARTICLE

Search of technological solutions aimed at reducing the number of image defects in a hybrid SWIR device

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Abstract

Objectives. The primary aim of this study is to minimize image defects in a hybrid photodetector with a sensitivity range of 0.95–1.65 µm, based on an InP/InGaAs photocathode. In order to achieve this, the surface quality of the photocathode must be improved prior to lift-off photolithography. In addition, the photolithographic process must be made highly reproducible.

Methods. In order to achieve this goal, a series of experiments on surface cleaning and improvement of the lift-off photolithography process were conducted. The following surface preparation methods were tested: chemical etching of the InGaAs surface; coating the photocathode surface with a protective photoresist layer before cutting the plate; using various photoresist removal methods (in dimethylformamide and plasma); and mechanical surface cleaning. In order to improve photolithography, experiments were conducted on drying times and photoresist methods, exposure and development modes were varied, and photoresist was replaced.

Results. Samples manufactured using the improved technology demonstrate a more than ninefold reduction in the average percentage of defects on the photocathode surface from 0.317% to 0.035%. Thanks to the improved quality of the photocathode surface, the image in the finished device is more uniform and the number of image defects significantly decreased. The process is highly reproducible.

Conclusions. Improvements in surface preparation technology, coupled with a reduction in the thickness of the photoresist used in lift-off photolithography lead to greater uniformity of images in hybrid devices and fewer defects. The proposed approach can be used for the mass production of high-sensitivity near-infrared hybrid photodetectors, making them competitive with those produced elsewhere.

Keywords: SWIR photodetectors, InP/InGaAs photocathode, surface cleaning of InGaAs, lift-off photolithography

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НАУЧНАЯ СТАТЬЯ

Поиск технологических решений, направленных на снижение количества дефектов изображения в гибридном приборе ближнего инфракрасного диапазона

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Резюме

Цели. Основная цель работы – уменьшение дефектов изображения, получаемого в гибридном фотоприемнике с диапазоном чувствительности 0.95–1.65 мкм на основе фотокатода из фосфида индия/арсенида галлия-индия (InP/InGaAs). Для этого необходимо улучшить качество поверхности фотокатода перед взрывной фотолитографией, а также обеспечить высокую воспроизводимость фотолитографического процесса.

Методы. Для достижения поставленной цели проведена серия экспериментов по очистке поверхности и по усовершенствованию технологического процесса взрывной фотолитографии. Для подготовки поверхности опробованы следующие методы: химическое травление поверхности InGaAs, покрытие поверхности фотокатода защитным слоем фоторезиста перед резкой пластины, использование различных способов удаления фоторезиста (в диметилформамиде и плазме), внедрение механической очистки поверхности. Для усовершенствования фотолитографии проведены эксперименты со временем и способами сушки фоторезиста, проведено варьирование режимов экспонирования и проявления, заменен фоторезист.

Результаты. Изготовленные по усовершенствованной технологии образцы демонстрируют более чем девятикратное снижение среднего процента дефектов от общей площади поверхности фотокатода по сравнению со старыми образцами: с 0.317% до 0.035%. Благодаря улучшению качества поверхности фотокатода изображение в готовом приборе стало более однородным, количество дефектов изображения значительно уменьшилось. Обеспечена высокая воспроизводимость процесса.

Выводы. Усовершенствованная технология подготовки поверхности, а также уменьшение толщины фоторезиста, используемого во взрывной фотолитографии, привело к увеличению однородности изображения в гибридном приборе, а также к уменьшению дефектов. Предлагаемый подход может быть применен при серийном производстве гибридных высокочувствительных фотоприемников ближнего инфракрасного (ИК) диапазона и позволяет им быть конкурентоспособными с мировыми аналогами.

Ключевые слова: фотоприемники ближнего ИК-диапазона, InP/InGaAs-фотокатод, очистка поверхности InGaAs, взрывная фотолитография

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INTRODUCTION

One of the popular imaging ranges is the short-wave infrared (SWIR) spectral diapason. Its radiation has properties similar to the radiation of visible range. SWIR is also promising in a variety of applications due to its unique features:

- transparency of some materials in the SWIR diapason[1];
- use of invisible radiation as illumination (nightglow, laser radiation with a wavelength of 1.55 μm, which is safe for human eye) [1];
- ability to distinguish objects with the same color in the visible range [2];
- compared to the visible range, the ability to observe at longer distances and in poor visibility (smog, rain, fog) [3].

Cameras operating in the near-infrared diapason have a wide range of applications both in scientific research, as well as in the civil and military-defense industries. For example, in the electronics industry, they are used for defect identification in printed circuit boards and solar panels[2]. In the food industry, they are used to inspect the quality of products [4]. In the military-defense industry, they are used for reconnaissance and tactical operations to detect camouflaged objects and track them [5]. In medicine, they are used for non-invasive tissue analysis and visualization of subcutaneous tissues [6].

Hybrid photodetectors operating in the SWIR are promising photosensitive devices. They consist of a photocathode and a solid-state electron-sensitive element (anode) in a single vacuum volume (Fig. 1). The photocathode operating in the pass-through mode absorbs photons. Thus electron-hole pairs are generated inside its volume. The electrons then move to the surface, then emit into the vacuum where they are accelerated by the electric field. The electron sensitive anode registers the electron flux, the intensity of which is directly proportional to the intensity of radiation absorbed by the photocathode.

This type of a device operates on the basis of an external photoelectric effect, so there is a need to locate such a system in vacuum conditions. Signal amplification is an advantage over solid-state analogs due to the generation of a large number of electron-hole pairs in the anode volume by accelerated electrons. It is also worth noting that the hybrid devices have a high level of variability in the types of possible photocathodes [8–10] and anodes within a single structure.

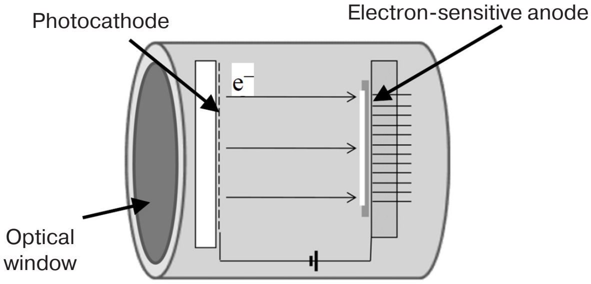

Fig. 1. Diagram of the hybrid photodetector device [7]

In this work, InP/InGaAs heterostructure (wavelength range of 0.95–1.65 μm) is used as a photocathode. Aa metal layer (electrode) is deposited on its surface to form a Schottky barrier, in order to transfer the photocharge from the active layer of the photocathode to the emitter layer with a larger band gap. When an external voltage is applied, the barrier between the active and emitter layers decreases, and photoelectrons are able to travel into the emitter and then into vacuum [11, 12]. The surface is activated with a Cs/O layer [13, 14], in order to reduce the work function of electron from the photocathode surface into the vacuum gap.

Lift-off photolithography is used to create a metal electrode. However, the contamination of the surface of the photocathode with small and large particles causes complications during the photolithography process. Large and small particles prevent the creation of a uniform electrode during photolithography. This can lead to image defects in the hybrid photodetector device. These particles are also visible in the final image from the device (Fig. 2).

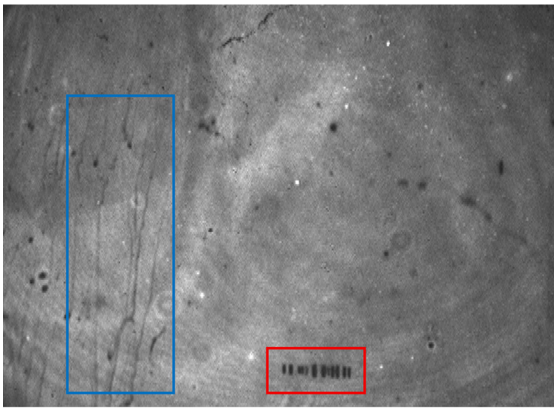

Fig. 2. Image defects caused by surface contamination and inhomogeneity of the electrode

Defects can be observed in the area marked with a red rectangle (Fig. 2) showing the non-uniformity of the electrode. The black rectangular areas are metal residues not removed during lift-off photolithography.

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[1] Edmund Optics. What is SWIR? https://www.edmundoptics.com/knowledge-center/application-notes/imaging/what-is-swir/?srsltid=AfmBOopNG8OgK_q1N35-W5tpY9aS7jqGYNeYN3mLq96-xOienoMu9u2T. Accessed June 04, 2025.

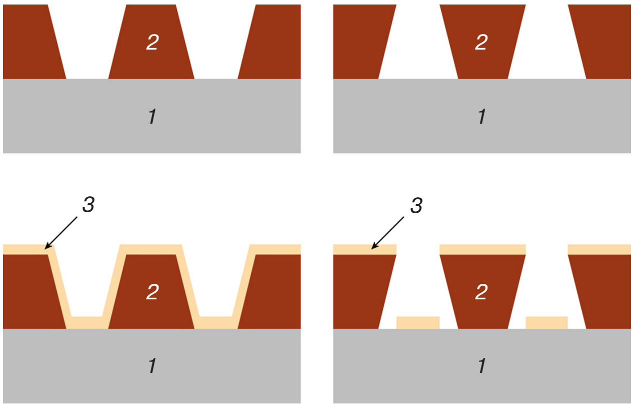
[2] HWYL En-Vision Technology. SWIR Cameras: What Are They? [Imaging & Application Guide] https://hwyl.in/swir-cameras/. Accessed June 10, 2025.

Dark lines are visible in the area bounded by the blue rectangle. These are assumed to be traces of a brush used to remove metal residues after photolithography. In [15], the presence of dark dots and lines in images from image intensifier tubes in visible and infrared ranges is associated with the photocathode surface contamination.

NRI "Electron"[3] uses substrates with an InP/InGaAs heterostructure in the production technology of a hybrid SWIR-range photodetector. A single wafer can be used to create photosensitive areas for up to four devices. Due to the fragility of the wafer, it must be cut before the photolithography process. Various small and large particles are adsorbed on the surface during cutting. These particles must be removed because they prevent contact during exposure and therefore increase the percentage of image defects. In addition, for the best operability of photocathodes with negative electron affinity, an atomically clean surface is required [16]. This will ensure the uniformity of Cs/O layer deposition for surface activation [17]. Moreover, the atomically clean surface increases the lifetime of the photocathodes [18].

A suitable cleaning technique must be found to remove contaminations from the surface of the photocathodes, in order to improve the image quality from the hybrid photodetector device. Several cleaning methods are available: chemical cleaning, plasma cleaning, and ion cleaning. Chemical cleaning is the most attractive method due to the low cost and ease of the process. Acidic solutions are widely used for etching of III–V group semiconductors. Among acidic etchants, the hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2) solution (HCl/H_2O_2) is considered one of the most suitable, since it provides the lowest degree of anisotropy during etching [19, 20]. An increase in the H_2O_2 concentration in etchant solutions leads to a significant growth in the etching rate [21]. This is not desirable for our applications, since it can change the thickness of the outer epitaxial layer of the heterostructure. Therefore, low concentrations of H_2O_2 must be used, in order to ensure low etching rates. In [20] a solution of HCl + H_2O_2 + ADS (ammonium dodecyl sulfate) was proposed for the purposes of the more efficient purification of nanoparticles from the InGaAs surface. The addition of ADS reduces the zeta potential of the surface, leading to a decrease in the particle's adsorption [20].

In addition to surface contamination, lift-off lithography was not successful in every experiment (it is not always possible to remove the excess metal layer completely to form the desired pattern). Possible reasons for this may be the use of a positive photoresist which creates an overcut border profile (Fig. 3a). The metal layer deposited on the walls of the photoresist prevents the penetration of the solvent used to remove the photoresist and the metal film. This makes the process of lift-off difficult or impossible. In general, negative photoresists are used in lift-off photolithography which create an undercut border profile (Fig. 3b). They help remove excessive metallization.[4]



(a) (b)

Fig. 3. Schematic diagram of the photoresist walls: (a) overcut border profile, (b) undercut border profile, where *1* is the substrate, *2* is the photoresist, and *3* is the metal

In order to use negative photoresists, the photomask must be modified and the solvents replaced. This requires additional technological development. The study of such technological changes is the subject of future research.

This article presents the results of experiments on surface cleaning after cutting, and selection of the optimal sequence of actions for getting the best cleaning of the photocathode surface. The results of experiments aimed at improving the reproducibility of lift-off photolithography process are also presented. A new photoresist was selected and by means of its use, lift-off occurs on each sample.

1. MATERIALS AND METHODS

Previously, the photocathode surface preparation and subsequent photolithography were performed as follows:

- manual cutting of a two-inch InP/InGaAs photocathode plate into 20 × 22-mm samples;
- cleaning plates in deionized water in the ultrasonic unit UZU-0.25 (Ulyanovsk Instrument Manufacturing Association, USSR) for 5 min;
- during the photolithography process, a positive photoresist FP-9120-1.0 (NIOPIK, Russia) with 1.1–1.3 µm thickness was used;

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[3] https://www.niielectron.ru/ (in Russ.). Accessed September 25, 2025.

[4] Image reversal (lift-off) photoresist FPN-20-ISO. https://www.frast.ru/obrashchennaya-vzryvnaya (in Russ.). Accessed September 25, 2025. (In Russ.).

- photolithographic operations (exposure and development) and deposition of the metal layer with subsequent lift-off were carried out on different days.

1.1. Surface preparation before photolithography

Surface cleaning experiments were performed on InP/InGaAs photocathodes, as well as on silicon wafers with a diameter of 3 inches.

A number of experiments were carried out in the technological process of surface preparation, in order to reduce contamination on the photocathode surface:

1) etching of InGaAs surface with H_2O_2 + HCl + ADS solution with 0.001 M hydrogen peroxide, 0.05 M hydrochloric acid and 0.05 mM ADS;
2) automated cutting of photocathode into samples of 20 × 22 mm;
3) coating the photocathode with protective layer of photoresist before cutting;
4) removal of photoresist in dimethylformamide followed by plasma treatment to remove photoresist residues;
5) surface cleaning process: mechanical washing of the surface in deionized water, then cleaning in an ultrasonic bath for 5 min, mechanical washing in deionized water.

1.2. Photolithography process

The following experiments were performed, in order to improve the lift-off photolithography process:

1. Change of the photoresist drying modes:
   Infrared drying, drying on hot plate at $T = 105°C$ for 1 min, drying in the air forced convection oven at $T = 115°C$ and different exposure times: 3, 5, 10, and 20 s. For certain photocathodes, a method of creation of an undercut border profile was tested. After exposure, the plate was additionally dried: for 1 min on the hot plate for one and for 5 min in the air forced convection oven for another.
2. Change of exposure modes (different exposure duration, different power) and, accordingly, of the development (different developer concentration and development time).
3. Reduction of the time, spent by the sample between the processes of exposure, development, metal deposition and lift-off.
4. Usage of the different positive photoresist with a smaller film thickness: FP-9120-0.4 (NIOPIK, Russia) with thickness of 0.4 μm instead of FP-9120-1.0 with thickness of 1 μm.

1.3. Visualization of experiments

Images of the samples were obtained with MBS-1 (Lytkarinsky Optical Glass Factory, USSR) and NORGAU NVM-2010 (NORGAU, Russia) optical microscopes.

A test bench was used to obtain the image from the device at uniform illumination. The block diagram is shown in Fig. 4.

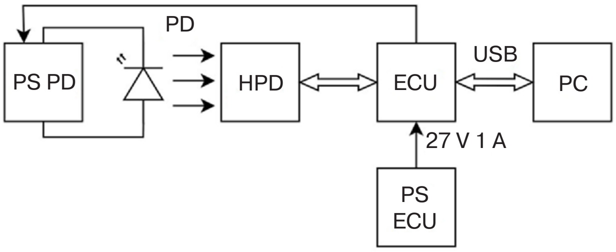


Fig. 4. Block diagram of the test bench for getting an image from the hybrid photodetector, where: PS—Power Supply, PD—Photodiode with a center wavelength sensitivity at 1.55 μm, HPD—Hybrid Photodetector, ECU—Electronic Control Unit, USB—Universal Serial Bus, PC—Personal Computer for image display and control

2. RESULTS

Etching of the InP/InGaAs photocathode (manually cut) surface in the solution of H_2O_2 + HCl + ADS in an ultrasonic unit for 5 min did not show any particular result. The surface was not successfully cleaned from small and large particles. As can be seen in Fig. 5, only certain large particles were removed. It is possible that some may have changed their position on the surface.

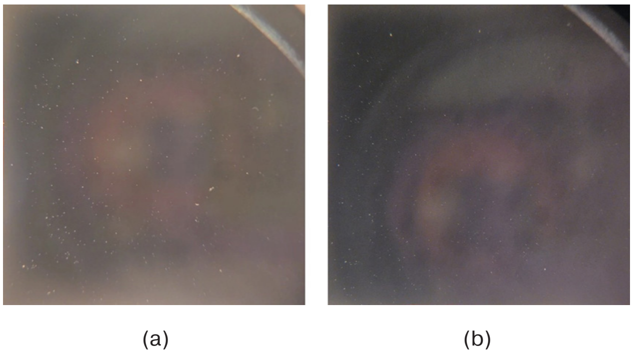
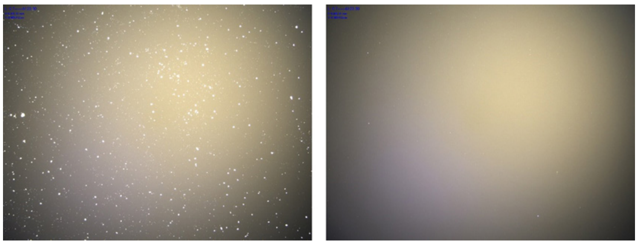


Fig. 5. InP/InGaAs photocathode surface: (a) before etching in H_2O_2 + HCl + ADS solution, (b) after etching. Field of view area 20 × 22 mm^2

A positive result was obtained when manual cutting was replaced by automated cutting. Automated cutting resulted in a significant reduction in the number of large particles adsorbed on the sample surface. Automated cutting led to a significant reduction in the number of large particles adsorbed on the sample surface (Fig. 6).

However, the surface still contains a large number of small particles of approximately 10 ± 5 μm in size (Fig. 7a). The number of such particles can be reduced by coating the sample surface with a photoresist before the cutting process (Fig. 7b). The number of small particles adsorbed on the surface during cutting is reduced. However, an oval shaped pattern appeared on the surface of the sample after coating with the photoresist and after its removal in dimethyl formamide. This pattern consists of small particles with a size of 10 ± 3 μm. These particles were not removed after the cleaning. These particles may not completely be removed with dimethylformamide.



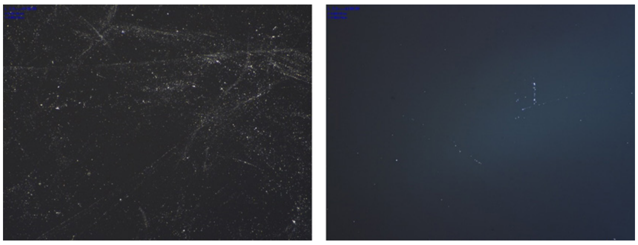
(a) (b)

Fig. 6. Si surface after (a) manual cutting, (b) automated cutting. Image taken at 0.7 magnification, field of view area 6.311 × 6.312 μm^2

(a) (b)

Fig. 7. Si surface after automated cutting: (a) without photoresist, (b) with photoresist. Image at magnification 2.0, field of view area 2.21 × 2.21 μm^2

These patterns do not appear when oxygen plasma is used to remove the photoresist [22]. However, as a result, the surface is insufficiently clean (Fig. 8).



(a) (b)

Fig. 8. Si surface after plasma-chemical etching: (a) not cleaned, (b) after cleaning. Image at magnification 2.0, field of view area 2.21 × 2.21 μm^2

Therefore, the following surface preparation method is used:

1) the initial two-inch wafer is covered with a layer of photoresist FP-9120-1.0;
2) then it is automatically cut into samples of the required size;
3) the protective layer of the photoresist FP-9120-1.0 is removed in dimethylformamide, then the photoresist residues are additionally removed in the oxygen plasma;
4) final cleaning of samples mechanically under the flow of deionized water after 5 min of the ultrasonic cleaning.

Changes in the photolithographic process (drying, exposure, development) did not affect the lift-off process. Excessive metallization was not removed. However, change in the photoresist thickness led to positive results.

Repeatability of the photolithography process can be achieved with the use of the new photoresist FP-9120-0.4 with a reduced level of thickness, and by means of the lift-off photolithography process (exposure and developing the pattern, metal deposition, removing excess metal) during one day. This could not have been achieved earlier. When using the previous thicker photoresist FP-9120-1.0, it was not always possible to remove metal completely, and thus create the necessary pattern on the photocathode surface.

The reduction in photoresist thickness is assumed to make its walls steeper. Therefore, the removal of metal (lift-off) occurs more successfully. It is reproduced at the moment of creating of a photosensitive region on each photocathode. This trend can also be observed in [23], where the photoresist walls became flatter as its thickness increased.

The photolithographic pattern obtained with use of the new technological approach is more uniform. It has fewer defects, compared to samples obtained with the use of the old technology.

Data analysis on the area and percentage of defects was carried out (Table), in order to quantify the effectiveness of the new technological approach. A sample of 12 photocathodes based on the new technological approach shows a low percentage of the number of defects from the area of the working area. N1–N12 are samples made with the use of the new technology, O1–O3 are samples made with the use of the old technology.

The average defect percentage using the modified technology for samples from the N1–N8 group was 0.086%, and for the N9–N12 group was 0.035%. This is 9 times lower compared to the indicator for the old technology group O1–O3 (0.317%). The standard deviation for the new technology is also significantly lower (0.039% and 0.019% *vs* 0.127%), which indicates a high reproducibility of the process.

Figure 9 shows that the working area of samples N9–N12 has the lowest percentage of defects. When preparing for photolithography, these samples were additionally mechanically cleaned after 5 min in an ultrasonic bath.

Table. Area and percentage of defects in the working area on the photocathode

Sample number	Total defect area, mm^2	Percentage of defects from the working area 130 mm^2, %
N1	0.059	0.05
N2	0.107	0.01
N3	0.073	0.06
N4	0.102	0.08
N5	0.080	0.06
N6	0.102	0.08
N7	0.031	0.02
N8	0.395	0.04
N9	0.020	0.02
N10	0.076	0.06
N11	0.020	0.02
N12	0.076	0.06
O1	0.349	0.27
O2	0.600	0.46
O3	0.288	0.22

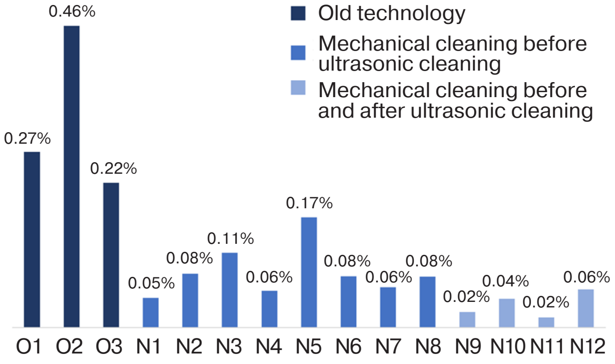


Fig. 9. Distribution of the defect fraction from the total area of the samples

Thus, the improved technological process not only reduces defects, but also provides more stable results in mass production.

Compared to Fig. 2, the quality of the image from the new device (Fig. 10) is significantly improved. The image has become more uniform, black dots from dirt are almost absent, and dark rectangles are completely absent.

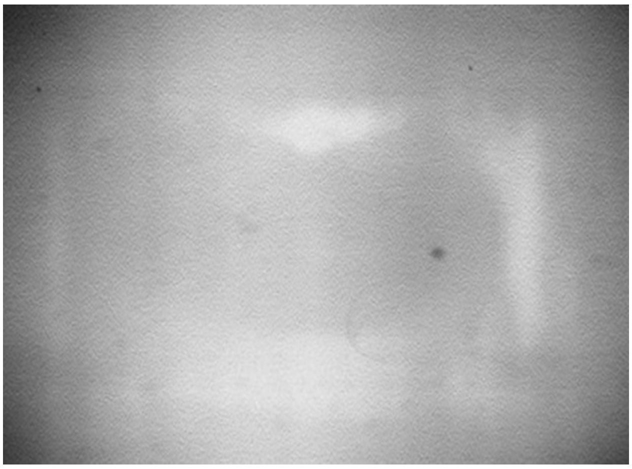


Fig. 10. Image of the device with a photocathode obtained using advanced technology

The results show that the reduction of the photoresist thickness and elimination of long-term interoperative sample storage significantly reduces the number of defects. The greatest contribution to quality improvement is made by a complex of measures: protection of the surface with a photoresist before cutting, the use of plasma cleaning; sequential execution of the stages of exposure; deposition and removal of the excess metal; as well as reduction of the used photoresist thickness.

The achieved level of the defect rate according to the photocathode measurements corresponds to the best world samples of the solid-state SWIR photodetectors IMX991 from SONY[5].

CONCLUSIONS

An improved technology of the surface preparation and photolithography processes for the hybrid SWIR photodetectors has been developed.

The average defect percentage was reduced by more than 9 times, from 0.317% to 0.035%. This corresponds to the best currently available world samples of solid-state SWIR photodetectors.

The image quality from the hybrid photodetector device is improved as a result, The image is more uniform, with fewer defects such as black dots, lines, and streaks.

A high level of reproducibility of the process is provided (reduction of the standard deviation by more than 6 times), enabling the proposed technology for mass production of the hybrid SWIR photodetectors to be scaled.

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Authors’ contributions

A.A. Egorenkov—formulating the aims and objectives of the research, scientific guidance and coordinating the research.

I.V. Danilova—interpreting the results, selecting technological routes for surface cleaning, practical testing and optimizing the modes on experimental samples, editing the article.

M.I. Bibinova—selecting technological routes of photolithography, practical testing and optimizing the modes on experimental samples.

S.N. Chelyshkov—conducting experimental measurements of sample parameters and deposition processes.

A.N. Vyaznikov—collecting, processing and statistical analysis of experimental data, preparing tables and samples.

K.S. Batalov—developing the experimental methods and verifying the obtained results.

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