InP/InGaAs photocathode for hybrid SWIR photodetectors

K J Smirnov, V V Davydov and Y V Batov

1 The Bonch-Bruevich Saint Petersburg State University of Telecommunications, Bolshevikov avenue 22/1, Saint Petersburg, Russia, 193232
2 OJSC “NRI “Electron”, Torez avenue 68R, Saint Petersburg, Russia, 194223
3 Higher School of applied physics and space technologies, Peter the Great Saint Petersburg Polytechnic University, Polytechnic street 29, Saint Petersburg, Russia, 195251

e-mail: kjsmirnov113@gmail.com

Abstract. The technology of creation the photocathode with quantum efficiency at the level of 5% based on the InP/InGaAs heterostructures is given. The effect of decreasing the quantum efficiency of the photosensitive structure on radiant sensitivity is considered. Several variants of realization of vacuum photoelectronic device with InP/InGaAs photocathode for special purposes are represented.

1. Introduction

At present time, photodetectors which operates in the spectral region of 0.9–1.7 μm (SWIR) find a various application in field of science and technique. Short-wave infrared video cameras based on InGaAs arrays developing actively. However, the characteristics of the sensitivity and threshold exposure of such cameras are insufficient for a number of special purposes, such as, recording the reflected infrared radiation in poor visibility conditions, a number of methods of non-destructive testing, refractometry, location [1-4]. Also should be noted that radiation sources, in particular sources for infrared spectral region, at present time could be used in high-speed impulse mode. To reveal advantages of such lasers, they need appropriate receivers [5-9]. Vacuum photoelectronic devices which include a photocathodes allow to provide significantly higher sensitivity indices due to the internal amplification as compared to the solid semiconductor detectors for SWIR. IR detectors on the basis of flip-chip technology (method for connection photon-sensitive semiconductors to external circuitry (CCD, CMOS) with solder bumps that have been deposited onto semiconductor surface) have a number of technological limitations, which makes their production extremely high-tech and therefore expensive as compared to vacuum photodetectors. In case of the detecting signals in 0.9–1.7 μm spectral range, the InP / InGaAs heterostructure [10-11] could be used as the photocathode which is implemented on the principle of inter-valley electron transfer (transfer electron photocathodes – TEP).

2. Formation and characteristics of InP/InGaAs photocathode

The photocathode is a heteropair of indium phosphide - indium gallium arsenide, grown by the methods of chemical vapour deposition of organometallic compounds (MOCVD) on a 350 μm InP substrate. To form the structure of the Schottky barrier on the surface, which is necessary for the
creation of transferred electron photocathode, Ti was deposited. The titanium electrode was a grid-structured with a thin of 300 angstroms. To create an effective photocathode, Cs and O2 molecules were deposited on an atomically clean InP / InGaAs heterostructure with a Ti electrode in an ultrahigh vacuum [12–15].

As a result of the activation process of the photocathode structure, results on the level of a few percent quantum efficiency were obtained (Figure. 1) [10]. In particular, at a wavelength of 1500 nm, quantum efficiency of activated InP/InGaAs heterostructure more than 5% was obtained.

![Figure 1. Spectral characteristics of InP/InGaAs heterostructures at a bias voltage Uc = 3V.](image1)

![Figure 2. Quantum efficiency of the InP / InGaAs photocathode depending on the irradiance at the bias voltage: 1 - Ub = 2.3 V; 2 - Ub = 2.0V.](image2)

The characteristic in figure 1 is measured with the help of monochromator. At a wavelength of 1500 nm, radiation power was 1.56 x 10^-6 watts. Effect of reducing the spectral sensitivity of the photocathode structure by increasing the power of the incident radiation was found out. Dependence of the quantum efficiency of the InP / InGaAs photocathode on the incident radiation applied to the sensitive structure at various bias voltages is shown in figure 2.
This effect could be explained by the accumulation of electrons in the surface layer of the InP emitter of the photocathode heterostructure [16-17]. Possibility of an electron to exit the emitter layer and to overcome a vacuum level can be estimated at no more than 10% at average. Electrons which were not emitted into vacuum remains in the electron-emitting layer, and further deposited in the near-surface region between the emitter and the metal contact. As a result of this effects accumulated electrons discharge in area near Schottky barrier. This leads to the suppression of emission properties and, consequently, sensitivity to radiation. The following solutions may be suggested to solve this problem: changing the physical characteristics of the InP emitter, increasing the active emission region of the photocathode relative to the area of the grid electrode [16], using of a signal attenuation system in photoreceiver modules with an InP/InGaAs sensor.

3. Design of hybrid device with InP/InGaAs photocathode

The developed heterostructures can be used in hybrid photosensitive devices which contain the photocathode and an electron-sensitive element in one vacuum volume [18]. Proposed technology makes it possible to obtain greater sensitivity as compared to the existing semiconductor detectors due to the internal amplification of the device. Such amplification could be achieved by applying high voltages to the cathode – anode section (photoelectron detector), which makes it possible to transfer energy to electrons of several kiloelectron volts. The “accelerated” photoelectrons further decelerates in the layer of the solid-state photoelectron detector, generating electron-hole pairs. It makes possible to obtain an internal gain in the device up to $10^3$ times. In case of silicon required energy for formation of one electron-hole pair is ~ 3.5 eV. Therefore, for ideal conditions electron bombarded gain is equal to 2200 times. Using this technology of electron-bombarded semiconductors (EBS) allows to create various special purpose devices [11, 18-21]. Typical disadvantages inherent in vacuum devices are minimized in the proposed detector due to the lack of classic amplification cascades (dynode lines) and microchannel plates (MCP). Due to the use of hybrid technology it is possible to exclude disadvantages introduced by alignment through fiber optics, which is inherent in the first generation of electro-optical converters. The device design is shown in figure 3. It is unified, type of the photodetector depends on the choice of the type of electron converter, the type of contact board and the photocathode structure. Currently, work is underway in 3 different areas depending on type of the photoelectron converter.

Devices on the basis of pin-diode arrays, where lines and matrixes of pin-diodes made of silicon and bombarded by electrons from the back side (“back side illuminated”), could be used as photoelectron converters. Use of diode technology allows to detect infrared radiation with a time resolution of less than 10 ns, with dark current on the elements of the diode array less than 100 nA. The advantages of this type of photodetectors should be used in onboard systems for fast-moving objects scanning. This will avoid a number of shortcomings inherent in existing scanning systems, such as low horizontal scanning frequency, significant form-factor parameters, and an insufficient level of reliability.

![Figure 3](image-url)
On the basis of the InP/InGaAs photocathode, ultrahigh sensitivity devices could be created. In such devices a pin-diode with an avalanche amplification technology (SPD APD) uses as an electron converter. Avalanche multiplication of effective carriers in the structure of the diode makes it possible to obtain an additional gain on the level of $10^2$ times at the output of the sensor. Photodetector with avalanche silicon diode allows to achieve spectral sensitivity of several hundred A/W at a wavelength of short-wave spectral region.

Hybrid technology of the IR cameras design allows to significantly increase sensitivity as compared to solid-state detectors made of InGaAs structures. In this case, an electron bombarded back side charge coupled device (EBCCD) offers as a photoelectron detector. The matrix has own spectral sensitivity in the visible range (VSR), typically it is spectral region from 400 to 900 nm. Therefore, for optical transparent photocathodes such as Cs$_2$Te, hybrid photodetectors got multispectral characteristics. In case of the InP/InGaAs/InP heterostructure suppression of the signal from photons with energy equal to VSR occurs automatically due to the optical properties of the InP.

The InP substrate has an extremely low level of optical transmission of photons with energy corresponding to the spectral range up to 900 nm. The creation of devices with SWIR photocathode and EBCCD is the most difficult because of the requirements not only to the sensitivity of the photocathode and the absence of defects in the CCD matrix, but also to the uniformity of the photocathode structure, as well as to low values of the dark emission current per cm$^2$.

To test the developed devices with different photoelectron converters, a unified measuring system could be used. It contains a high-voltage power supply unit, as well as a system for connecting and reading the video signal from the device output. The block diagram of the connection of the developed photodetector to the photoreceiver module is shown in figure 4.

![Figure 4](image)

**Figure 4.** Functional scheme of measuring system for hybrid photodetectors: 1 — photodetector, 2 — amplifier, 3 — filter, 4 — analog-digital converter, 5 — level converters, 6 — synchrngenerator, 7 — voltage driver, 8 — USB interface, 9 — high-voltage power supply, 10 — controls, 11 — 27 V. supply, 12 — computer.

4. Conclusion
The development of InP/InGaAs photocathode with high parameters of quantum efficiency, uniformity and low dark current level opens up a great opportunity for creating a line of special-purpose instruments for detecting signals of the spectral range of 0.9-1.7 microns. The hybrid technology of device formation provides internal amplification on the level of $10^3$ times. It allows to rely on significantly better parameters of detectability as compared to existing instruments of similar purpose.
5. References

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