Vacuum-semiconductor hybrid photoelectric device for near IR-region

V I Zubkov¹, D E Mironov² and A V Solomonov¹

¹ SpbSETU “LETI”, Saint-Petersburg, Russian Federation
² JSC “Electron”, Saint-Petersburg, Russian Federation

E-mail: vzubkovspb@mail.ru

Abstract. Results of the development of a hybrid vacuum semiconductor photodetector for the near IR-range are presented. The device is based on InP/In₀.₅₃Ga₀.₄₇As/InP photocathode and electron-sensitive CCD matrix with the number of elements 768x580. In order for the minority charge carriers generated within 0.5 µm from the surface to reach the recording cells, the CCD matrix was thinned to about 30 µm. In addition, in the reverse side of the matrix the phosphorus impurity was implanted. This technique creates the necessary gradient of the electric field, which provides high efficient transport of minority charge carriers to the potential pits of the CCD matrix. At room temperature and continuous irradiation the measured threshold irradiance was registered at the level of 5·10⁻⁸ W/cm² for the wavelength range λ = 1–1.5 µm.

1. Introduction
Many photodetectors are currently used for visualization, detection, environmental analysis, navigation, astro orientation, earth surface sensing, etc. [1, 2]. Often, they are subject to increased requirements, both on the detection range of the object, and the possibility of detecting ultra-weak signals. Among all photoelectric devices, a special place is occupied by vacuum hybrid radiation detectors, which have the ability to register almost single photons. This class of devices combines vacuum and microelectronic technologies in one device. This significantly complicates the design and somewhat increases the size of the device, but allows you to achieve unsurpassed characteristics in sensitivity and speed. The improvement of the parameters of the hybrid devices is performed by use of new semiconductor materials, by the expansion of the spectral range and the transition to matrix principles of image recording. This article presents the results of research and development of a hybrid device designed to detect weak near-IR signals.

2. Concept of hybrid photoelectric device
Solid-state photodetectors use the phenomenon of internal photoelectric effect for their work [3]. Photons falling on the sensitive surface of the semiconductor are absorbed in it, resulting in the generation of non-equilibrium electrons and holes that occupy free states in the allowed energy bands – conduction and valence. Detection and amplification of the non-equilibrium part of the charge carriers is the task of such solid-state photodetectors. In contrast, vacuum photodetectors are based on the use of an external photoelectric effect [1]. Here, the absorbed photons knock electrons from the semiconductor into vacuum. For this to happen, the electron work function from the material must be small. To this end, its surface is usually covered with a thin (monatomic) layer of cesium oxide. This technology essentially requires placing the active photodetector layer in a high vacuum (<1·10⁻⁹ Pa),
since Cs has a record oxidizing capacity among all elements and is instantly oxidized in air. Technically, this is implemented inside a pumped quartz flask with an input glass of a material having a necessary range of transparency.

One of the first vacuum photoelectric devices was photoelectron multipliers. Using a system of successive dynodes in them it is possible to achieve a gain of $10^6$. In modern hybrid devices adopted the principle of “proximity” (parallel propagation of electrons from the cathode to the anode), there is no focusing of electrons and the system of dynodes, thereby significantly reduced the size of the device. High gain is achieved by selecting modern semiconductor materials and compounds with high quantum yield and high drift electron mobility.

3. Implementation of hybrid IR-photoelectric device

The principal design of the developed vacuum-semiconductor hybrid photoelectric device is shown in figure 1. Infrared photocathode is located in close proximity to the input window of the photodetector. The photon absorbed photoelectrons are emitted from the opposite side of the photocathode facing inside of the hybrid device. There they are accelerated by a uniform electric field to the energy of several keV. The electric field is created by applying a voltage of 6–9 kV between the photocathode and the silicon anode. Note that it implements almost electrostatic conditions with typical currents of a few nA.

![Figure 1. Principal design of vacuum-solid state hybrid photoelectric device:](image)

The photocathode is a semiconductor lattice-matched heterostructure InP/InGaAs/InP [4]. Active region for absorbing photons is a layer of In$_{0.53}$Ga$_{0.47}$As having thickness of 2–3 microns. The direct structure of the energy bands of the active region and InP-barriers forms the sensitivity range of the photocathode, which comprises 0.95...1.65 microns.

Photoelectrons propagating with acceleration in the vacuum gap of a hybrid device bombard the anode surface, causing the generation of an electron-hole pair. As the anode in this case, we use an electron-sensitive CCD matrix with number of elements 768x580, turned to the electronic flow by the reverse side (back-illuminated electron-bombarded CCD-matrix). On average, the energy of 3.6 eV is spent on the birth of an $e$-$h$ pair, so one high-energy electron, moving inside silicon, can produce several hundred pairs, thus providing a high gain of the hybrid device. In figure 2 the results are presented of calculations of the propagation of electrons with energy 11 keV in Si, showing the relative number of electrons propagating to different depths in the silicon target. As you can see, the depth of penetration of electrons is about 0.4 microns. Some (several %) part of the photoelectron flux is reflected from the surface of the silicon wafer.

In order for the minority charge carriers (electrons) generated within 0.5 µm from the surface to reach the recording cells, the CCD matrix was thinned to about 30 µm. In addition, on the reverse side of the matrix the phosphorus impurity was implanted. This technique creates the necessary gradient of the electric field, which provides high efficiency of transport of minority charge carriers to the
potential pits of the CCD matrix. The structure of the energy bands of the photocathode and the schematic design of the anode are shown in figure 3.

Figure 2. Relative number of electrons penetrating different depths into the silicon target (a); the energy of the embedded electrons as a function of the penetration depth (b).

Figure 3. Band diagram of photocathode (a); Cross section of the anode and the charge carrier profile in it (b): 1 – the reverse side of the CCD matrix; 2 – profile of implanted impurity; 3 – CCD cells.

The surface of the photocathode was activated by CsO in the Riber-M installation, which reduced the electron work function from the semiconductor and provided greater external quantum efficiency of the heterostructure. The impurity implantation into the reversed CCD matrix was carried out to a depth of about 1 µm. The profile of the majority charge carriers was measured using an ECV profilometer [5]. The peak concentration was $2 \cdot 10^{19}$ cm$^{-3}$.

4. Conclusion
In this study we present the results of the development of a hybrid vacuum semiconductor photodetector for the near IR range. The device is based on InP/In$_{0.53}$Ga$_{0.47}$As/InP photocathode and electron-sensitive CCD matrix with the number of elements 768x580. At room temperature and continuous irradiation the measured threshold irradiance was registered at the level of $5 \cdot 10^{8}$ W/cm$^2$ for the wavelength range $\lambda = 1–1.5$ µm.
References
[1] Rogalski A 2012 Progress in Quantum Electronics 36 342
[2] Grundmann M 2006 The physics of semiconductors (Springer-Verlag, Berlin, Heidelberg)
[3] Sze S M and Kwok K Ng 2007 Physics of semiconductor devices (John Wiley & Sons)
[4] Bell R L, James LW and Moon R L 1974 APL 25(11) 645
[5] Yakovlev G E, Frolov D S, Zubkova A V, Levina E E, Zubkov V I, Solomonov A V, Sterlyadkin O K and Sorokin S A 2016 Semiconductors 50(3) 320