Investigation of the quantum efficiency degradation over time for InGaAs photocathodes in hybrid devices for near infrared spectral range

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Abstract. The structure and operating principle of InGaAs photocathode in near-IR hybrid photo device are considered. The mechanisms leading to the degradation of the quantum efficiency of the photocathode are being studied. The rate of the quantum efficiency degradation of the photocathode is measured for three hybrid devices. The methods to reduce the degradation of the photocathode sensitivity are suggested.

The hybrid devices under investigation are designed to operate in the wavelength range 0.95-1.65 μm. In this regard, the In₀.₅₃Ga₀.₄₇As semiconductor solid solution with a band gap of 0.75 eV was chosen as an active (illumination-absorbing) layer. The heterostructures In₀.₅₃Ga₀.₄₇As / InP have perfect crystall lattice matching, that is, they are an ideal heteropair. Besides, when such a photocathode operates in transmission mode, the InP substrate acts as a filter that cuts off the radiation with wavelength less than 0.9 μm. The band structure of such a photocathode is shown in figure 1.

The absorbing layer must have a low concentration of free electrons in absence of illumination to reduce the dark current, so it must be a p-type semiconductor. The layer, emitting photoelectrons into vacuum, should also be a p-type semiconductor. In order to apply a bias to the interface between these two layers, there must present a barrier for holes. Our photocathode uses a metal-semiconductor system to form a Schottky barrier.

To reduce the work function of electron from the photocathode surface into vacuum gap, the surface is activated with a Cs-O layer. The relatively small band gap (1.34 eV) and degree of doping of the emitter layer InP (no more than 10¹⁷ cm⁻³) do not allow reaching the negative electron affinity (NEA) in the true sense, but, nevertheless, allows to reduce the vacuum energy to value of 1 eV.

The principle of the photocathode operation is shown in figure 2. Infrared radiation, passing through the InP substrate, is absorbed in the InGaAs layer, thereby transferring electrons from the valence band to the conduction Г-valley, where they cool down. Then these electrons diffusely move into the InP emitter layer, which is depleted due to the positive potential at its surface. The electric field in the emitter layer is 10⁴ V/cm, but less than the breakdown field (10⁵-10⁶ V/cm). It is known, that in such fields the conduction band electrons in InP get energies close to the energies needed for the transition to the higher valleys. The L-valley of the conduction band is 0.53 eV above the minimum of the Г-valley. At the surface these valleys have a height relative to the Fermi level of the Schottky barrier (Ti/p-InP) of about 1 eV, while the barrier itself has a height of 0.8 eV. Thus,
electrons from the upper InP valleys can escape into vacuum from the surface activated by the Cs-O system.

One of the most important problems of such photocathode is the degradation of activating layer characteristics over time, which occurs due to the vacuum level decrease in the system. In paper [1], devoted to study of the Cs-O layer, deposited on the p-InP surface, was reported about the decrease in the quantum efficiency of such structure due to the rearrangement of cesium peroxide into its superoxide, which reduces the dipole moment of the system (figure 3), and subsequent oxidation of the InP surface.

The cited work also presents comparative dependences of the decrease in the photocurrent of the activated InP photocathode depending on the vacuum level. They clearly showed how strongly the initial vacuum level affects the life of such a photocathode (figure 4).

Comparing the above mentioned dependences, it could be seen that when the vacuum level decreases by 4 times, the time during which the photoemission current decreases by an order of magnitude also decreases by 4 times.

In accordance with the purpose of the study, it was necessary to ensure the invariability of the experimental conditions for a long time. The greatest influence on the IR photocathode photocurrent is exerted by bias voltage $U_{bias}$, irradiance, and measurement geometry.

To achieve the constancy of the above parameters, a unit was developed and created, which is a “black box” with an incandescent lamp placed inside it (in a separate compartment). An interference filter for $\lambda=1.06 \mu m$ was used to create a monochromatic irradiation. Extraneous light was blocked by the walls of the “black box” and the lamp compartment, which were pasted over with black photographic paper to reduce light reflection; individual elements have been painted in mat black
paint. The radiation from the lamp, passing through the hole in the wall of the compartment, to which the interference filter was tightly pressed, created at the entrance window of the device uniform irradiation over the area in the spectral sensitivity range of the IR photocathode. The lamp was powered with an accuracy of 0.01 A by a GPR-1810-HD stabilized power supply. The luminous flux density at $\lambda=1.06 \, \mu\text{m}$ was determined with standard photocell FD №84 and was $2\times10^{-7} \, \text{W/cm}^2$. To reduce the relative measurement error in the presented results, the experimental data taken at one lamp filament current were used. The invariability of the measurement geometry was ensured by a tool that guaranteed the location of the device in a given place in the box. During the measurements, the box was covered with a black lid and an additional black cloth on the top. $U_{\text{bias}}$ was supplied to the photocathode by DPS 3003 DC-DC converter powered by a 12 V battery, capable of operating at a potential up to 6 kV or more and having accuracy of 0.01 V. In addition to $U_{\text{bias}}$, the voltage $U_{\text{acc}}=-1$ kV was applied to the photocathode. The photocurrent was measured in the anode circuit at zero potential with digital amperemeter. The current measurement error was 0.005 nA.

In the interval between measurements, the devices were subjected to other tests with application of biases and illumination; for all devices the storage was the same: in a nitrogen atmosphere at room temperature, in a dark place (without absolute darkness). The measurement results are shown in Fig. 5.

Figure 5 shows that the device №8 has a high degradation rate of the quantum efficiency in the period up to 100 days. Quantum efficiency of devices №5 and №6 was not measured in the period of 100 days under “black box” conditions. For devices №5 and №6, the rate of decrease in sensitivity over the period of more than 100 days was about 0.12% per day. In work [2], devoted to degradation of the sensitivity of NEA photocathodes based on epitaxial single crystals of GaAs, it was shown that the main factor affecting the sensitivity decrease is the vacuum level, and, especially, the partial pressure of O$_2$ molecules and molecules containing oxygen: CO, CO$_2$, and probably H$_2$O. Due to the lack of accurate data on the preservation of the InP photocathode sensitivity, and taking into account that GaAs and InP belong to the same group of A$^3$B$^5$ direct-gap semiconductors and can both reach the NEA state, in future, for comparison, the data of this article will be used, where the rate of decrease in the sensitivity of GaAs NEA photocathode in vacuum of $1.5\times10^{-9}$ Pa for 20 days is about 0.34% per day (figure 6).

The time dependence of the quantum efficiency can be described by the formula:

$$QE(t) = QE_0 e^{-t/\tau},$$

where $\tau$ is the time during which QE of the photocathode will decrease by a factor of e, $QE_0$ is the initial quantum efficiency.

\[\text{Figure 5. Photocathode quantum efficiency dependence on the storage time at different bias.}\]

\[\text{Figure 6. Dependence of GaAs NEA photocathode quantum efficiency on the time spent in dark in the unit chamber with vacuum of } 1.5\times10^{-9} \, \text{Pa [2].}\]
Calculation using this formula for NEA GaAs photocathode gives a lifetime of 6500 h or 270 days [2]. A similar calculation for devices №5 and №6 for the entire period of measurements gives the lifetimes 750 and 780 days, respectively. According to similar estimates, the lifetimes of each of the devices reach more than 5 years. It is not yet clear what is the reason for the relatively large decrease in the sensitivity of devices №5 and №6 in the middle of the curve (120-180 days), it is possible to be an error of the measurements. An increase in the sensitivity of device №5 in the range of 280-340 days might be associated with a change in the photocathode CVC as a result of the application of large $U_{bias}$ during pulse studies.

A traditional way to increase the lifetime of photoemission devices is to provide a deeper vacuum in them. The glass, used to make device packages, is one of the best vacuum materials. However, inclusions of graphite that are baked into the surface of the glass from graphite molds, in addition to deteriorating electrical insulation properties, presumably worsen the vacuum level inside the device. When a high voltage is applied to the photocathode, additional gases can be released from the graphite particles due to their stimulation by high-voltage leakage currents. In the course of the work, technological methods for the manufacture of packages and methods of their chemical cleaning were developed, significantly reducing the inclusions of graphite. It is structurally desirable to reduce the inner surface of the device and, possibly, to increase the getter sorption surface. Technologically, a rather long (more than 15 hours) preliminary heat of the device body is required at high temperature (up to 400°C) in high vacuum. For manufacture of devices №5, №6 and №8 more gentle mode of heating the bodies and entrance windows to temperature of about 320°C for 10 hours was used, due to the fact, that high temperature can worsen the parameters of the anode unit.

A definite resource for increasing the lifetime of IR photocathode is provided by a larger $U_{bias}$. As can be seen from figure 5, raising $U_{bias}$ by 0.4 V almost doubles the quantum efficiency and thus can compensate in some degree the sensitivity drop. However, this resource is limited, since simultaneously with the increase in the quantum efficiency, the dark current of the photocathode does increase. The dark current of IR photocathode is a sum of the dark current of temperature-generated electrons in the InGaAs layer and of electrons generated by impact ionization in InP. If the first component of the dark current little depends on $U_{bias}$, then its second component very strongly depends on the electric field strength and at a certain stage of increasing $U_{bias}$ can begin to significantly exceed the useful signal.

Most photocathodes have a definite lifetime associated with the amount of charge flowing through them, so the static mode of operation is not optimal for them. In this regard, at the moment, the experiments are also being carried out concerning the operation in various pulse modes. Thanks to pulsed activation of the photocathode and pulsed illumination, it is possible to extend their resource, associated with the flowing charge, by 2–3 orders. In addition, this opens up the possibility of supplying large $U_{bias}$ without the risk of rapid degradation of the photocathode sensitivity and, according to the preliminary data, makes it possible to increase the quantum efficiency by a factor of 2.5 and more, relatively to the limit in the static mode.

References
[1] Pianetta P, Lee D, Sun Y et al. 2007 InP Transferred Electron Cathodes: Basic to Manufacturing Methods Grant №DAAD19-02-1-0396
[2] Chanlek N, Herbert J D, Jones R M et al. 2014 Journal of Physics D: Applied Physics 47 5 1–7