High sensitive InP emitter for InP/InGaAs heterostructures

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Abstract. Results of indium phosphide structures research, showing the possibility of using in the near infrared range (NIR) photocathodes of InP / InGaAs, are represented. An optimal method of obtaining the atomically clean indium phosphide surface was suggested. The spectral characteristics of indium phosphide and InP/InGaAs heterostructure were given. Researches of the photoemission dependence of the structure with surface grid electrode upon different supply voltages were carried out.

1. Introduction

The creation of a photocathode, which operates in the NIR range, also known as the transferred electron photocathode, was proposed by Bell [1]. Such photocathodes can move the long-wavelength threshold of photoemission by increasing the internal energy of the photoelectrons (with the help of the metal electrode which is applied to the effective surface of the photocathode). This structure has been realized on the basis of heteropair indium phosphide – solid solution of indium – gallium arsenide. The InGaAs forbidden band is narrow enough to detect near–infrared range. This narrow–band material ("absorber") cannot provide by itself the negative electron affinity (NEA) on the surface, which is a determinant factor for obtaining a high quantum efficiency for such structures. However, InGaAs can be perfectly matched to the InP crystal lattice, which, being a conductor of electrons (emitter) generated in the absorber, allows to get on its surface the effective state of the NEA. Semiconductor photocathodes activated to negative electron affinity (NEA) serve as electron beam sources for many applications. InP photocathode is an emitter of InP/InGaAs heterostructure. These heterostructures as compared to other semiconductor materials allows getting greater quantum efficiency in case of detection reflective laser beam in near infrared range [2]. The purposes of the work were to develop the optimal method of obtaining atomic clean indium phosphide surface, to obtain high quantum efficiency of the InP samples, to research the increase of the photoemission with the help of titanium grid electrode and to apply the result of the researches for obtaining high sensitive InP/InGaAs photocathode.

2. Chemical cleaning of InP surface

The structures based on the indium phosphide are characterized by low thermal resistance and heating over with the temperature of 593 K lead to the degradation of these structures, so that the typical cleaning methods for metals and thermally stable materials cannot be used. Sulfur passivation leads to stable surface termination, but the chemisorbed sulfur atoms cannot be removed completely by thermal annealing at temperatures below the decomposition temperature of InP. Process of obtaining a clean InP surface is rather difficult, especially pre–vacuum chemical cleaning step. The treatment with HCl–C₃H₈O and subsequent vacuum annealing is useful method for obtaining the
atomically clean GaAs surfaces, another semiconductor of the A₃B₅ group [3]. However, etching with these chemical compounds is ineffective for InP surfaces.

Therefore, we used the efficient three-step method of chemical etching combined with a thermal cleaning in vacuum to obtain the atomic clean surface of InP [4, 5]. Samples of InP (111): Zn, with concentration \( p = 1 \times 10^{18} \text{cm}^{-3} \) were used for studies. Sample of InP structure with surface grid is shown in figure 1.

![Figure 1. InP structure with surface grid.](image)

Etching time was increased, as compared to [4], and the mode was adjusted in the direction of the removal rate increase of a thick natural oxide by the use of ultrasound in the etching process. Besides that the intermediate etching step was added: a weak solution of sulfuric acid was used. Strong acid solutions with HCl or H₂SO₄, which are used in third step of chemical cleaning, are able to remove the surface oxide and leave the InP surface passivated with elemental P which is, in turn, terminated with H. This yields a hydrophobic surface and allows lower temperatures to be used during annealing. All steps of chemical cleaning are shown in table 1:

| Solution | Concentration  |
|----------|----------------|
| 1        | H₃SO₄:H₂O₂:H₂O  | 4:1:100         |
| 2        | H₂SO₄:H₂O       | 1:10            |
| 3        | H₂SO₄:H₂O       | 1:1             |

Protective layer formed on InP surface are also allows to carry etched structures from chemical laboratory bench to vacuum installation in atmosphere. This is an important achievement in terms of surface oxidation and uncontrolled contamination of surfaces. We studied the effect of etching on the titanium grid and the possibility of etching agents use without degradation of the grid structure. As a result, we found that etching is equally effective for two different acid solutions HCl and H₂SO₄, however, in case of HCl titanium grid is exposed to chemical degradation. Indium phosphide is emitter of the InP/InGaAs heterostructures, accordingly chemical cleaning of this structures identical to the InP.
3. Activation of InP and InP/InGaAs structures

The ultra-high vacuum installation was used to conduct the research in a vacuum, which could reach the level of \(1 \times 10^{-9}\) Pa. Structural diagram of installation is shown in figure 2.

![Figure 2.](image)

**Figure 2.** Structural diagram of the ultra-high vacuum installation: 1 – nitrogen valve, 2 – trunk-line, 3 – molecular sieve foreline trap, 4 – ion pump’s valve, 5 – ion pump, 6 – trunk-line valve, 7 – manipulator, 8 – entry gate, 9 – gate valve, 10 – loading chamber, 11 – press and housing preparation chamber, 12 – special vacuum press, 13 – viewport, 14 – activation chamber, 15 – sources of Cs and \(\text{O}_2\), 16 – sapphire viewport.

As a result of the etching process the hydrophobic surface InP structure was obtained [4]. After heating in a vacuum chamber at a temperature of about 573 K, the net InP atomic surface was received, that’s ready for the activation with Cs and \(\text{O}_2\), which allows to form effective state of NEA on InP photocathode surface.

The method of the activation structure called «yo-yo» [6], based on a continuous simultaneous supply of cesium and oxygen was used. The process for obtaining the maximum photoemission current was about 90 minutes. The progress of activation is presented in figure 3.

![Figure 3.](image)

**Figure 3.** Activation of structure etched by 1. \(\text{H}_2\text{SO}_4\). 2. \(\text{C}_3\text{H}_8\text{O}+\text{Br}\). 3. \(\text{C}_3\text{H}_8\text{O}+\text{HCl}\).

Research was conducted on InP structures which etched by solutions of \(\text{C}_3\text{H}_8\text{O}+\text{Br}\), \(\text{C}_3\text{H}_8\text{O}+\text{HCl}\) and our new three stage method of chemical cleaning with solutions of \(\text{H}_2\text{SO}_4\). After graphical analysis, we found that the results of photoemission current using the new method of
chemical cleaning increase 6 times as compared to previous experiments. In addition to pure samples were also studied samples with the grid electrode, used to create the photocathode with the transferred field. The dependence of the photoemission current on the applied bias voltage is shown in figure 4.

![Figure 4. The dependence of photoemission current on the applied bias voltage.](image)

Measurements were carried out in range of 500 to 950 nm. Based on figure 3, quantum efficiency (QE) is calculated using the ratio:

$$QE = \frac{I \cdot h \cdot c}{P \cdot e \cdot \lambda} \cdot 100\%$$  \hspace{1cm} (1)

Where $I$ — the photoemission current, $P$ — the monochromator radiation power at wavelength $\lambda$, $h$ — the Planck’s constant, $c$ — the speed of light $e$ — the elementary charge.

Calculation of the dependence between QE and $\lambda$ using (1) are represented in figure 5.

![Figure 5. Spectral characteristics of InP:Zn (111) photocathodes, p=1·10^{18} cm^{-3}. 1 – without grid; 2 – with grid on $U_r= 0$ V; 3 – with grid on $U_r= 1.2$.](image)

We managed to get quantum efficiency greater than 10% at a wavelength of 630 nm, and more than 1% for 900 nm on indium phosphide. In [5] the QE at 632 nm was in the range 9-12% and spectral characteristics were not present. The photolithographic grid stamped on of InP, has demonstrated not only the overall photoemission gain increase, but also provided the greater sensitivity at longer wavelengths when a voltage was applied to the grid with the help of the pressure contact. For example at the wavelength of 650 nm the QE increases by 46%, and by 177% at 900 nm.
The resulting dark current was small (less than 0.05 nA at \( U_r = 3 V \)), but at the applied voltage exceeding 2V the photoemission current has saturation, which makes the voltage increase weakly effective. However, operation mode of the surface grid electrode significantly depends on technical features of it creation. We are going to create titanium electrode with optimal operating level on 8-10 supply voltage.

Results of the investigations of indium phosphide were applied on InP/InGaAs heterostructures, which were grown by MOCVD methods. Heteropair indium phosphide – solid solution of indium – gallium arsenide was realized on substrate InP with thickness 350 mkm. Etching and vacuum annealing were conducted identical to InP structures Spectral characteristics of the InP/InGaAs heterostructure with developed surface grid titanium electrode are shown in the Figure 6. Analyzing obtained dependencies (fig. 6), we found that quantum efficiency of the proposed heterostructure, which operates in reflection mod, reaches 4% at the wavelengths from 900 to 1600 nm. This result is more than 2 times greater than results of previous researches. Quantum efficiency level of structures, which work in transmission mode, was worse than reflection mode. This is important problem for creation real device with those structures. It is connected with non-optimal parametres of the substrate. Theoretical calculations were shown that with the optimal substrare dependence between QE in radiation and transmission mode below 15%.

![Figure 6. Spectral characteristics of InP/InGaAs, 1 – with grid at \( U_r = 2 V \); 2 – with grid at \( U_r = 3 V \)](image)

4. Conclusion

The heterostructures of InP/InGaAs work in near infrared range and could be used in devices for special purposes, where high processing speed of detection reflected radiation of special laser systems,( for example quantum-dot lasers) from the object is needed [7]. At present time, solid-state analogs of these devices cannot provide the same processing speed. The received results showed that the developed structure parameters are not optimal. The further increase of QE can be achieved by the optimization of heterostructures InP/InGaAs thickness and the basic carrier concentration.

References
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