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## SHOTTKY BARRIER OPTICAL SPECTROMETER ON GRADED-GAP SEMICONDUCTORS

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### АННОТАЦИЯ

Проанализирован и изучен экспериментально оптоспектрометрический эффект в варизонной m-s-структуре, в которой имеется изменение ширины запрещённой зоны $E_g$ в плоскости m-s-перехода и в направлении, неопендикулярном ей.

Обсуждается оптоспектрометрический эффект для случаев, когда световой поток направлен на m-s-переход через широкозонный полупроводник и показано, что зависимость фототока такой структуры от координаты светового потока воспроизводит спектральный состав этого потока.

На основе анализа были созданы спектрометрические элементы; они изготавливались химическим осаждением Au на поверхности варизонных кристаллов n-$Ga_{1-x}Al_xAs$, выращенных на подложках из n-GaP методом жидкостной эпитаксии. Барьерный контакт (m-s-переход) был расположен на косой поверхности варизонного кристалла $Ga_{1-x}Al_xAs$, а световой поток падал к m-s-переходу со стороны его широкозонной части через GaP.

Таким образом, создан иполупроводниковый оптический спектрометр, в котором спектрометрический элемент, изготовленный на основе варизонной Au-n-$Ga_{1-x}Al_xAs$/ n-GaP структуры, выполняет функции диспергирующего элемента, выходного коллиматора и приёмного элемента. Такое совмещение нескольких функций в одной варизонной m-s-структуре осуществлено впервые, причём этот элемент имеет крайне малые габариты и вес.

Рабочая спектральная область спектрометрического элемента 1,45-1,90 эВ, предельное спектральное разрешение 0,02-0,05 эВ.

### ABSTRACT

The optical spectrometric effect in the graded m-s structure, which has alteration of band-gap zone $E_g$ in the space of m-s junction and in its perpendicular direction, have been analyzed and studied experimentally.

Discussed optical spectroscopic effect for cases where the light beam is directed in m-s-junction through a wide gap semiconductor and it is shown that the dependence of the photocurrent of this structure to the coordinates of the luminous flux reproduces the spectral composition of this stream.

Based on analyze, there have been created the spectrometric elements. They were manufactured by the chemical deposition of Au onto the surface of the graded gap crystals $n - Ga_{1-x}Al_xAs$ which was expressed on substrate from n-GaP by the method of liquid epitaxy. The barrier contact (m-s-junction) was placed on slanting surface of the graded gap crystal $n - Ga_{1-x}Al_xAs$ and light steam fell on the m-s junction from the its direction of the wide gap part through GaP.

Thus, a semiconductor optical spectrometer was created, in which a spectrometric element made on the basis of a graded-gap $Au - n - Ga_{1-x}Al_xAs/n - GaP$ performs the functions of a dispersing element, an output collimator, and a receiving element. Such a combination of several functions in one graded-gap m-s structure was carried out for the first time, and this element has extremely small dimensions and weight.

Working spectral region of the spectrometric element is 1.45-1.90 eV and ultimate spectral resolution is 0.02-0.05 eV.

**Ключевые слова:** полупроводниковый оптический спектрометр, спектрометрический эффект, варизонная m-s структура, m-s переход, варизонный слой $Ga_{1-x}AI_xAs$, барьерный контакт, нанослой золота, спектрометрический элемент, аппаратная функция, предельное спектральное разрешение.

**Keywords:** semiconductor optical spectrometer, spectrometric effect, graded-gap m-s structure, m-s junction, graded-gap layer $Ga_{1-x}AI_xAs$, barrier contact, gold nanolayer, spectrometric element, hardware function, ultimate spectral resolution.

1. INTRODUCTION

Semiconductor hetero graded-gap barrier structures based on multicomponent solid solutions are now widely used to create various optoelectronic devices [1, 2].

Intensive research of semiconductor hetero-structures based on graded-gap $A^3B^5$ crystals has significantly expanded the opportunities of using graded-gap surface-barrier (m-s) structures on which various fundamentally new devices are created, such as selective photodetectors [3] and spectrometric elements [4, 5]. Spectrometric element – a semiconductor optical spectrometer based on the optospectrometric effect in a graded-gap semiconductor. This effect is due to the coordinate dependence of the optical properties of the graded-gap semiconductor. Two types of spectrometric elements based on graded-gap semiconductors are known. One of them is created on a graded-gap p-n structure [6] and the other based on a graded-gap m-s structure [4, 5, 8].

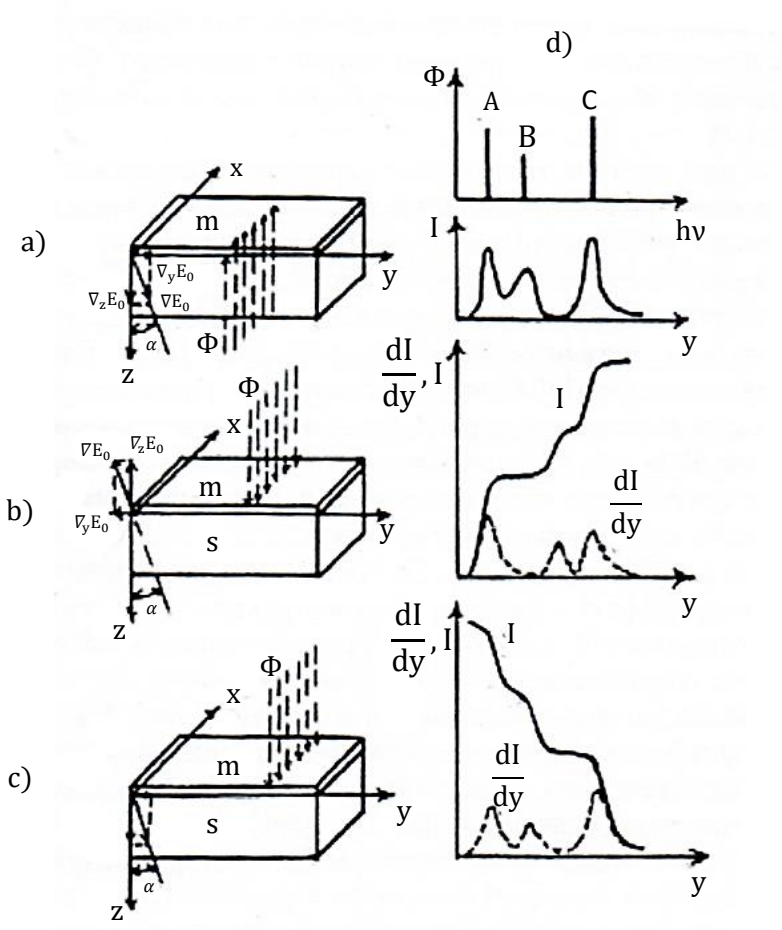


*Fig.1 Design diagram of graded-gap m-s structures for observing the optospectrometric effect [4]. Scanning of light fluxes Φ was carried out along the plane of the m-s transition. The threshold energy of direct optical transitions $E_0$ differs in the direction of light propagation. a- $E_0$ is decreasing, semiconductor lighting, b- $E_0$ is increasing, semitransparent layer metal lighting, c- $E_0$ is increasing, semitransparent layer metal lighting, d-spectrum of the light flux Φ, 1-photocurrent I, 2- dI/dy.*

The optical spectrometric effect in the graded-gap m-s structure consists in the fact that depending on the direction of the incident light flux Φ, the dependence of the photocurrent I on the coordinate y or the dependence of the derivative of the photocurrent (dI/dy) on y reproduces the spectral composition of the light flux. The paper [4] discusses three possible options for obtaining the optospectrometric effect in m-s structures by changing the band gap $E_g$ or the threshold energy of direct optical transitions $E_0$ along the m-s **transition** plane.

In the first case, the light flux Φ is directed to the m-s-junction through the semiconductor and $E_0$ decreases in the direction of light propagation (picture 1. a). In this case, like in the opto-spectrometic element based on the graded-gap p-n structure, monochromatic light is absorbed and generates electron-hole pairs locally in the vicinity of the plane in which $E_0$ is close to the photon energy hν. For a small width of the light

flux and small values of the diffusion-drift lengths of minority carriers, electron-hole pairs will produce a photocurrent I if the light flux is directed to the intersection line of this plane with the m-s junction plane. The dependence of the photocurrent of the structure on the coordinate of a narrow light flux changing in the direction the projection of the vector $\nabla E_0$ onto the plane of the m-s junction turns out to be δ-shaped. If there are photons with different energies in the light flux, each energy will have its own absorption plane and own intersection line with the m-s transition plane.

In two cases, typical of the nature of the m – s illumination, the luminous flux Φ is directed to the m-s-junction through a semitransparent metal layer (Fig. 1, b, c). The absorption of light and the generation of electron-hole pairs occurs near the metal in the semiconductor layer, where$E_0 < h\nu$. In this case, the dependence of I on y for monochromatic light has the form of a threshold curve, and the δ-shaped form has a dependence of $dI/dy$ to y. Therefore, to reproduce the spectral composition of the light flux, it is necessary to use the dependence of $dI/dy$ on y, and the optical spectrometric effect in graded-gap m-s structures for the light flux directed to the m-s transition through the semitransparent metal layer can apparently be called differential. The differential opto-spectrometric effect in the graded-gap m-s structure in the case (Fig. 1, c) with increasing $E_g$ in the direction of light propagation was studied both theoretically and experimentally [4].

The aim of this work is to study experimentally the opto-spectrometric effect in a graded-gap m-s structure, for the case when the light flux is directed to the m-s transition through a wide-gap semiconductor (Fig. 1a) and to create a spectrometric element based on such a structure and study it properties.

In this case, if the light flux (Φ), containing photons of several energies, is focused into a narrow line and moved along the surface of the structure of the semiconductor (s) - metal (m) in the –direction y (Fig. 1a), then the dependence the photocurrent (I) from y should reproduce the spectral composition of the light flux (Φ), since in these structures the band gap of the semiconductor varies both in the direction perpendicular to the plane of the m-s transition and the plane of the m-s transition.

For obtaining satisfactory parameters of the spectrometric element based on the m-s structure with approximate coincidence of the directions of the light flux and the vector $\nabla E_0$, the absolute value of the gradient of the threshold energy of direct transitions $|\nabla E_0| = \gamma$ must be in the range

$$K_0\varepsilon \gg \gamma \gg \frac{\varepsilon}{L^+ + W} \qquad (1)$$

the inverse steepness of the absorption edge, L * is the diffusion-drift length of minority carriers in the decreasing direction W is the space charge layer width, K is the absorption coefficient).

The half-width of the hardware function, measured at half its maximum value, in the coordinates y and hν, is, respectively

$$\delta_y = 2{,}45\frac{\varepsilon}{\gamma \sin\alpha} \qquad (2)$$

$$\delta_\nu = 2{,}45\varepsilon$$

Comparing the hardware functions of spectrometric elements based on the m-s structure [4] and on the basis of the p-n-structure [5], we can see that they are the same in terms of form in the case of the same exponential dependence of K on hν. The spectral resolution of both elements for the same ε should be the same. However, in m-s structures due to the use of a semiconductor with one type of conductivity in them, smaller values of ε can be obtained than in p-structure. This can give the m-s structure an advantage in spectral resolution.

2. EXPERIMENT

The real spectrometric element is a variable $Ga_{1-x}AI_xAs$ m-s structure (Fig. 2), in which the x value varies along the m-s-transition and increases deep into the crystal; the direction $|\nabla E_o|$ is an angle $\alpha = 0.01 + 0.1\ \mathrm{rad/s}$ perpendicular to the plane of the m-s transition, and the quantity $|\nabla E_o| = \gamma = 20 \div 80\ \mathrm{eV/sm}$. In the m-s junction plane, the threshold energy of direct optical transitions ($E_0$) varies from 1.45 to 1.92 eV and $E_0 = E_g$, because the graded-gap $Ga_{1-x}AI_xAs$ solid solution at $E_0 = 1.92$ eV is direct-gap.

Such a graded-gap m-s-structure and based on it a spectrometric element were created as follows. At first, a graded-gap layer $n - Ga_{1-x}Al_xAs$ was grown by liquid-phase epitaxy while cooling in the atmosphere $H_2$ on an n-GaP substrate oriented along the (111) crystallographic plane. The graded gap $Ga_{1-x}Al_xAs$ crystals were n-type, the difference in the concentrations of ionized donors and of acceptors $n = N_d - N_a$, determined from the capacitance – voltage characteristics, was $(0.5–6)\cdot 10^{16}\ \mathrm{sm^{-3}}$ at 300 K. [7] The x value of the grown crystal was the largest at the interface with the substrate, $0.4 \div 0.5$ and gradually decreased in the direction from the substrate to a value of $0.02 - 0.05$. The thickness of the graded-gap layer was $80 - 100$ μm. Then, an oblique section with a length of 4.5 mm was made on the graded-gap layer and mechanical and chemical polishing. Then an ohmic contact was created in the melting of an alloy of 97% In + 3% Te into an epitaxial layer of $n - Ga_{1-x}Al_xAs$ beyond the oblique section in the $H_2$ atmosphere.

In this paper, we report on the creation and study of the characteristics of spectrally selective coordinate-sensitive spectrometric elements based on a graded-gap m-s structure. For spectrometric elements, $Au - n - Ga_{1-x}AlxAs / n - GaP$ structures were used, in which the active layer $Ga_{1-x}Al_xAs$ was graded, and their bandgaps $E_g$ changed in two directions, as in the m-s-junction plane and in the direction perpendicular to it

(Fig. 2). T he barrier contact Au, creating the m-s junction, was located on the oblique surface of the graded-gap Ga crystal, $Ga_{1-x}Al_xAs$. Before chemical deposition of the gold (Au) layer, the oblique surface of the graded-gap $n - Ga_{1-x}Al_xAs$ layer was treated with a 4% V g + 96% $CH_3OH$ bromomethanol etchant [3]. The thickness of the barrier contact of the gold nanolayer was 10-15 nm. To improve the properties of the heterointerfaces between the $n - Ga_{1-x}Al_xAs$ active layer and the GaP substrate, a buffer layer of variable composition $Ga_{1-x}Al_xAs_{1-y}P_y$ with x and y, varying between $0.38 \leq x \leq 0.45$ and $0.04 \leq y \leq 0.20$ was created by the method of [8]. This layer leads to an improvement in the photoelectric characteristics of the active layer of $Ga_{1-x}Al_xAs$ ($0.04 \leq x \leq 0.38$) and the spectrometric element. The ohmic contact (In + 4% Te) is located on the surface of p- $Ga_{1-x}Al_xAs$, and the (In) terminal is located on the surface of the Au layer. The light flux Φ was directed to the m-s junction through the n-GaP substrate.

Spectrometric elements were mounted in the Threshold photodiode housings in such a way that they could be illuminated from the semiconductor (GaP) side. Electrical installation was carried out with a silver wire with a diameter of 0.1 mm, which was soldered to an ohmic contact and to a layer of gold outside the oblique thin section of indium at a temperature of $150 - 200\,^{\circ}C$ in air. The spectrometric element operated in the photoelectric generator mode. All measurements were carried out at room temperature.

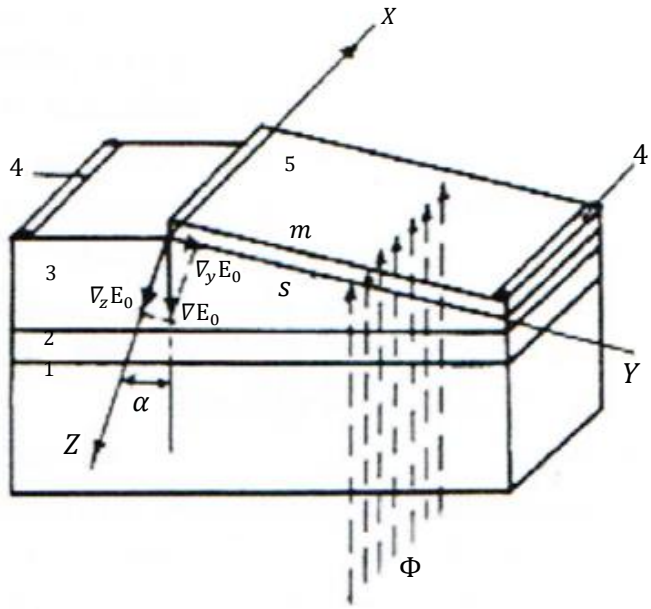


*Fig. 2. The real construction of a spectrometric element based on a graded-gap $Ga_{1-x}Al_xAs_{1-y}P_y$ m-s structure when illuminating the m-s – junction through a semiconductor. Scanning of light fluxes Φ was carried out along the plane of the m-s transition. 1-substrate (GaP), 2-buffer layer ($Ga_{1-x}Al_xAs_{1-y}P_y$) , 3-graded-gap crystal ($Ga_{1-x}Al_xAs$), 4-Omical contact (In+4%Te) and outlet (In), 5-barrier contact (Au)*

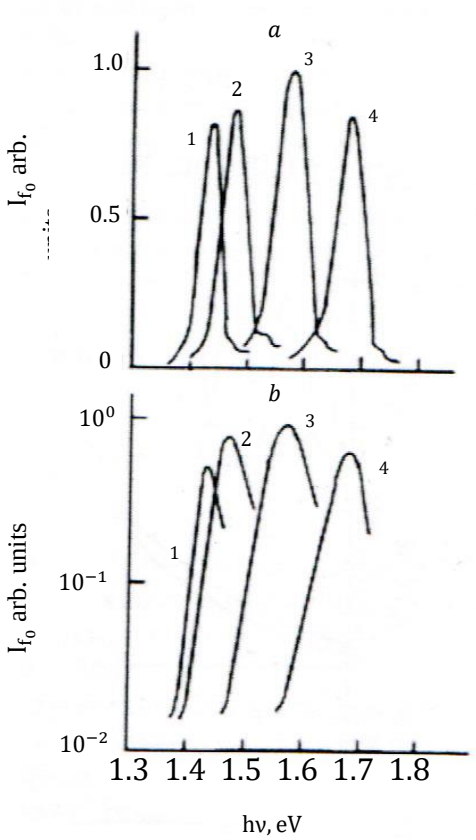


*Fig. 3. Spectral dependences of photocurrent ($I_{f_0}$) of a spectrometric element based on a graded-gap Ga_(1-x) Al_x As m-s structure in linear (a), semi-logarithmic (b) scales for various values of the coordinate y, mm: 1-0; 2-0,7; 3-1,4; 4-2,1.*

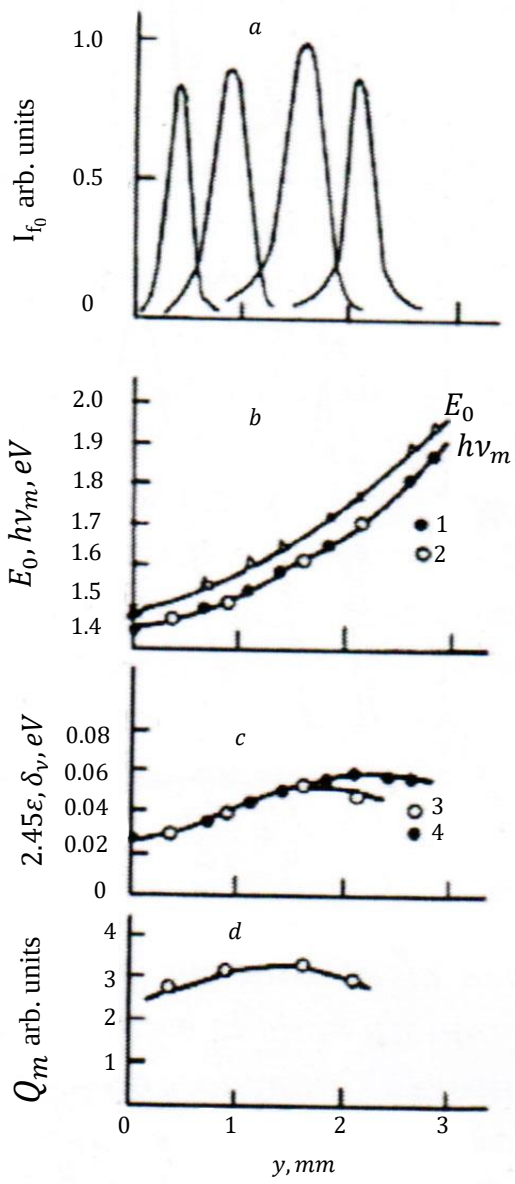


*Fig. 4. The instrument function $I_{f_0}(a)$, the dispersion curve ($h\nu_m$) and the threshold energy of direct transitions $E_0$ (b), the half-width of the apparatus function $\delta_\nu$ (c) and its amplitude $Q_m$ (d) for the spectrometric element based on the $Ga_{1-x}Al_xAs$ m-s-structure .1 - from the dependence $I_{f_0}$ for y = const, 2- from the dependence $I_{f_0}$ for $h\nu = const$, 3 - experiment, 4 - calculation.*

The size of the spectrometric element along the y axis was $\sim 3 \div 6$ mm, in the direction perpendicular to the yz plane $\sim 1.5 \div 2$ mm, and along the z axis $\sim 0.3 \div 0.4$ with an GaP substrate. The technique for measuring the optical spectroscopic effect is described in detail in [4, 6].

Using a spectrometric element, the spectrum of a neon lamp (TH-0.2) was recorded to assess the quality of the reproduction of the spectrum of the light flux containing a large number of spectral lines. In this case, the light source — a neon lamp — was placed in the place of the monochromator and installed near an adjustable optical slit. The axis of the slit was perpendicular to the y plane. The spectrometric element was moved by an electric drive in the y direction, perpendicular to the optical axis. When the spectrometer element was illuminated from the side of the wide-gap semiconductor (Fig. 2), the dependence of the photocurrent I on the photon energy hv was measured for a fixed y and I for y for a fixed hv.

3. RESULTS AND DISCUSSION

An experimental study of a spectrometric element based on an $Au - n - -Ga_{1-x}\,Al_xAs / n - GaP$ structure under illumination from n-GaP (Fig. 2) was as follows. First, the spectral dependences of the short-circuit photocurrent $I = I_{f_0}$ for various fixed values of the coordinate y were studied. The results of these studies were used to determine the dependence of $E_0$, $\varepsilon$ and the instrumental function on y, as well as the dispersion curve.

Secondly, we investigated the dependence of $I_{f_0}$ on y for various fixed photon energies hν. From these studies, the real apparatus function was determined as a function of y and the dispersion curve.

Thirdly, using a spectrometric element, the spectrum of a neon lamp was recorded to assess the quality of the reproduction of the spectrum of the light flux containing a large number of spectral lines.

In the first and second cases, the light flux was created using a prismatic monochromator IKM-1 (or DMR-4) with an incandescent lamp (SI-300-10, KIM-75-9). In the third case, to record the spectrum of the TN-0.2 neon lamp, it was placed in place of the monochromator.

The spectral dependences of the photocurrent for several fixed values of y, as can be seen from Fig. 3a, are b-shaped, and their half-widths are 0.020 + 0.050 eV. The energy of the maximum of the photocurrent spectra gradually increases with increasing y from 1.44 to 1.9 eV (Figs. 3a, 4b).

For $h\nu < E_0$, the dependence of I on hν has an exponential region covering almost two orders of magnitude.The slope of this section was determined by the steepness of the absorption curve:

$$\varepsilon \cong \left(\frac{d\ \ln I_{f_0}}{dh\nu}\right)^{-1}$$

which was $0.013 + 0.020$ eV. As in [6], ε increases with x.

The dispersion and the hardware function were determined from the spectral dependence of the photocurrent for various sections of the element (for various fixed values of y). The hardware function, measured directly in the coordinates of y for various fixed hν, is shown in Fig. 4a, has a 5-shaped shape. The dispersion of the spectrometric element was determined by the dependence of $h\nu_m$ on y (Fig. 4b) by differentiating this dependence with respect to y. It should be noted that the dependence hν, $E_0$ gradually increases with increasing y (Fig. 4a). The difference $E_0 - h\nu_m$ is 0.04 - 0.06 eV.

The linear dispersion $dh\nu_m/dy \cong dE_0/dy$, the value of $dE_0/dy$ is $0.6 \div 1.4$ eV/cm, which corresponds to

$$\gamma = \frac{1}{\sin\alpha} \cdot \frac{dE_0}{dy} = 30 \div 70 \text{ eV/sm}$$

The experimental (∘ — 3) and calculated (•−4) half-widths of the apparatus function change with variation of y (see Fig. 4c). The half-width of the hardware function is $\delta = 0.02 - 0.05$ eV with a change in y within $0 - 3$ mm.

Quantum photosensitivity at maximum $Q_m$ with a change in y varies within ± 10% of its average value and amounts to $Q_m$ = 0.10-0.30 e./fot. (Fig. 4d). Changes in $Q_m$ with coordinate y are such that $Q_m$ is proportional to $|\nabla E_0|$.

In fig. Figure 5 shows the spectrum of a neon lamp recorded by a spectrometric element and the spectrum of the same lamp, recorded by a prism monochromator with a silicon photo diode. As you can see, the spectrum of a neon lamp is reproduced using a spectrometric element with an accuracy sufficient to determine the position and intensity of the main lines.

So, based on the graded-gap $Au - n - Ga_{1-x}Al_xAs/n - GaP$ structure, an optospectrometric effect was detected when the m-s junction is illuminated by the semiconductor.

Let us compare the real spectrometric element when illuminating the m-s junction from the side of the semiconductor with the model considered above [formula (2)].

Since the difference $E_0 - h\nu_m$ is positive and commensurate with the half-width of the hardware function in the coordinates hν, the main absorption of light in the element occurs in those parts of the crystal where $h\nu < E_0$, i.e. on the exponential portion of the absorption edge. However, the proximity of γto the maximum permissible $\gamma_{max}$ leads to the fact that for those sections of the crystal where γ is especially large (y> 1.5 mm), the short-wavelength slope of the instrumental function has a lower slope than theoretically calculated, and the half-width of the instrumental more than theoretically calculated (Fig. 4c). As can be seen, for y <1.5 mm, where $y < y_{max}$, the experimental value of the half-width of the hardware function is equal to the theoretical value of $\delta_\nu = 2.45$ s. The increase in measurements of the amplitude of the hardware function over the range is due to the fact that y depends on y. A decrease in y at the edges of the range leads to a decrease in the amplitude of the hardware [FUNCTIONS. As follows from theoretical calculations.

For y <1.5 mm, where $\gamma < \gamma_{max}$ when the conditions adopted when considering the model of the spectrometric element turned out to be fulfilled, the hardware function coincided with the theoretical one [4].

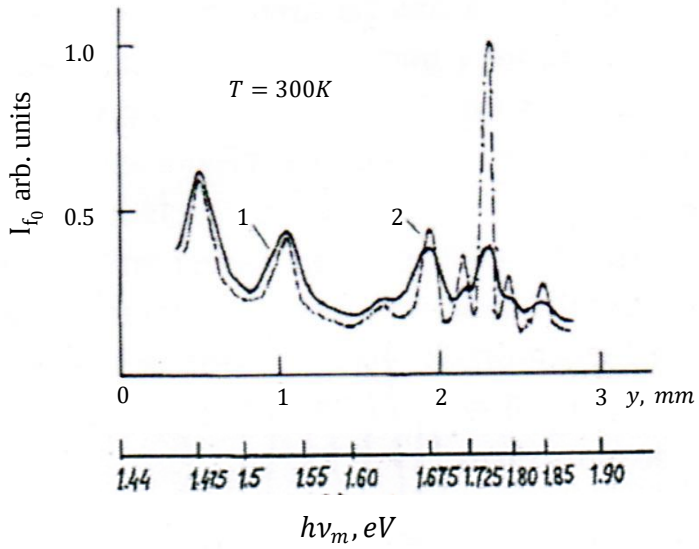


*Fig. 5. Spectrum of a neon lamp recorded spectrometrically which is based on a graded-gap $Ga_{1-x}Al_xAs$ m-s structure (1) and a prism monochromator (2). The luminous flux is directed at m-s -transition through a wide-gap semiconductor.*

4. CONCUSION

Thus, it can be stated that in a graded-gap m-v structure when illuminated by a wide-gap semiconductor, an opto-spectrometric effect is observed corresponding to the theoretical model. A spectrometric element based on a graded-gap m-s structure is a new type of semiconductor optical spectrometer that combines the properties of a dispersing element, an output collimator and a photodetector of optical spectrometers. Such a combination of several functions in one graded-gap m-s structure was realized for the first time.

Semiconductor optical spectrometer with a barrier allows one to record emission spectra with high sensitivity and resolution. Especially promising is the use of a semiconductor optical spectrometer in spacecraft due to its low weight and dimensions.

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