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The method of recording the photoemission current in the process of forming a photoemission coating

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A new method for recording photoemission current in the process of photocathode formation is presented, which allows, by fixing the photoemission signal without „parasitic" components in the form of leakage currents, ionization, thermal emission, to increase the quantum yield of the formed photocathode. The description of the method and the mode of its implementation is given. The results of experiments on the formation of a reflection photocathode Cs_3Sb using a new registration method are presented.

Keywords: photoemission material, photocurrent, reflection photocathode.

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Introduction

Formation of a photocathode is an indispensable part of fabrication of any vacuum photoelectronic device from the primitive photocells to the sophisticated streak tubes.

Practically all effective photocathodes (pure metal photocathodes are not considered) are either fully formed or at least activated in a vacuum environment using the photocurrent control method, i.e., the reaction of the photocathode to emission of a given spectral range corresponding to the sensitivity range of the formed material [1–3]. Since most of the devices are equipped with photocathodes based on alkali metal antimonides, we will continue to use the term „formation", meaning, among other things, the process of activating certain types of photocathodes using alkali metals.

In fact, the process of photocathode formation is a sequential or parallel-sequential deposition on a substrate of elements that form one or another photoemission material after reacting with each other, most often such elements are antimony, tellurium, alkali metals (Cs, K, Na), oxygen — with photo-response control, for which an accelerating voltage is applied between the photocathode substrate and the additional electrode, and the photoemission current is measured in the resulting circuit.

Most of the photoemission materials, except for A^3B^5 compounds are formed at temperatures exceeding normal conditions which at certain stage of the process or in case of some unfavorable process conditions leads to a significant rise of the so-called „dark current", i.e. rise of the signal level detected when the material being formed is not exposed to light. In a number of cases, this makes it impossible to see the photoemission current, since the dark signal becomes ten times higher (Fig. 1), and then the process continues with dark current control, which makes it impossible to clearly identify whether there is enough alkali metal, whether it needs to be drained or whether the exposure should be continued, and what is happening with the emission capacity of the photocathode. This approach leads to fabrication of a photocathode with an unfavorable composition and poor efficiency, which affects the yield level of suitable devices during their mass production, and also significantly increases the development time for new products due to the time spent on empirical selection of the „dark current" generation modes.

For example, when forming a photocathode of photoelectronic multipliers with sputtered dynodes, when some alkali metal antimonide is used as a material for secondary electron emission, the formation of both photoemission and secondary emission materials occurs simultaneously. However, the photocathode needs the light to pass through it and, hence, shall have a significantly lesser thickness,

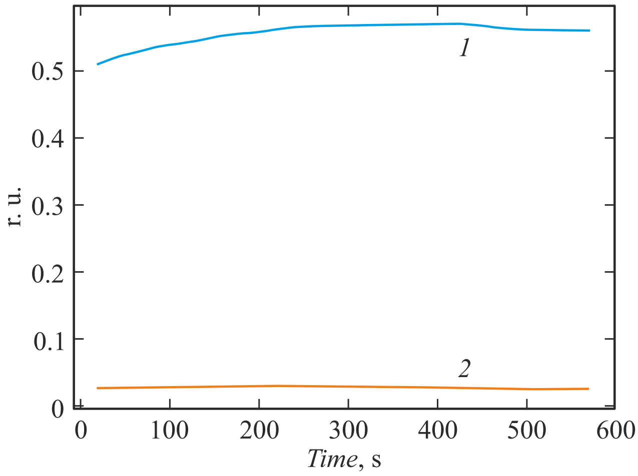

Figure 1. Graphs of changes in photoemission and dark currents when using classical detection method: *1* — total current, *2* — photoemission current.

compared to the secondary emission material of dynodes — as a result, a large amount of alkali metal accumulated during the process, which is necessary to work out the large thickness of the antimony layer pre-sprayed onto the dynodes and performed using the photocathode dark current, and thus, not allowing tracking the quality of the photocathode, leads to a shift in the process efficiency either towards photoemission (we will lose the gain of the device), or towards secondary electron emission (we will lose the quantum output of the photocathode and, as a result, the „signal-to-noise ratio").

The formation of bulk light-reflecting photocathodes also requires the application of a large amount of alkali metal to fully treat the pre-sprayed antimony layer. As a result, the photoemission current remains unknown for a rather long period of time, since it cannot be detected against the background of high values of the dark current, which makes it impossible to accurately determine the moment when optimal photocathode stoichiometry is obtained. The bulk photocathodes are often formed at temperatures above 200 °C, which is higher than the fracture temperature of the photoemission material [4], and, therefore, the alkali metal build-up is always accompanied by two opposing processes: formation of a chemical compound of the desired stoichiometry and thermal destruction of this compound. Therefore, it is required to correctly chose the moment of time when the device starts being cooled, and thus, define the photocathode condition when its is cooled to the temperatures when its destruction may no longer occur, and, consequently, define the resulting quantum yield of the formed photoemission material.

In addition to the examples described above, the problem of high dark current creates serious obstacles to the development of photocathodes formation based on alkali metal antimonides by method of molecular beam epitaxy [5], where to provide the molecular flow of antimony it is necessary to raise the temperature to 380 °C–400 °C.

Thus, today the task of photoemission current detection during the formation of photocathode is extremely relevant.

1. Structure of the detected photocurrent

During photocathode formation the detected photocurrent I_{Reg}, in fact, is an integral value combining the photoemission current I_F, insulator leak current I_L, thermal emission current allowing for electric field impact I_T, ionization current I_I, current induced by various fields I_{In}:

$$I_{Reg} = f(I_F, I_T, I_L, I_I, I_{In}).$$

Photoemission current — is the current generated by photoelectrons formed as a result of photoemission [6]. Photoemission current depends on the strength of electric field near the photocathode surface $E = U_a/L$, as well as power of radiation initiating the photoemission P

$$I_F = f_2(U_a/L, P, S),$$

where L — distance between the electrode-collector and substrate under the photocathode, U_a — voltage supplied to the collector S — sensitivity of the photocathode during detection to the wavelength of the incident radiation P.

Insulator leakage current — the current flowing in the photocurrent detection circuit, regardless of emission and ionization processes. The leakage current is proportional to the voltage U_a supplied to the detection electrode, and inversely proportional to the resistance of the insulator R:

$$I_L = f_3(U_a/R).$$

During photocathode formation, the resistance of the insulator can vary widely, both as a result of alkali metals deposition and formation of additional conductive zones, and as a result of eigen temperature dependence of the insulator material conductivity. In both cases, the resistance decreases much more strongly with insufficient techno-chemical preparation of the insulator for the photocathode formation process, since various contaminants may remain on it.

The ionization current arises as a result of photoionization and shock ionization (by photoelectrons) of alkali metal vapors and depends on spectral composition of radiation used to illuminate the photocathode, i.e. on the quantum energy $E_{h\nu}$ (radiation wavelength determines the quantum energy) for the photoionization case, on the electron energy at the moment of impact E_e in case of shock ionization, on the ionization energy of the alkali metal E_I, and, consequently, on the type of alkali metal, as well as on the partial pressure of this metal P_{Me} inside the formation zone of the photocathode defining the concentration of the metal molecules. Ionization current I_I can be roughly represented as the sum of the photoionization current I_{FI} and the shock ionization current I_{II} and is determined by the formula (1). In this case, the last component is the sum of the currents obtained during shock ionization by both photoelectrons I_{IIF} and thermionic electrons I_{IIT} and is determined by the formula (2):

$$I_I = I_{FI} + I_{II} = I_{FI} + I_{IIF} + I_{IIT}, \tag{1}$$

$$I_{II} = I_{IIF} + I_{IIF}, \tag{2}$$

$$I_{FI} = f_4(E_{h\nu}, E_I, P_{Me}),$$

$$I_{IIF} = f_5(E_{eh\nu}, E_I, P_{Me}),$$

$$I_{IIT} = f_6(E_{eT}, E_I, P_{Me}),$$

where $E_{eh\nu}$ — energy photoelectron, E_{eT} — energy of thermal electron.

Thermal emission current is defined by the number of electrons with its eigen energy higher than the potential barrier of the interface „solid–vacuum". The thermal emission current exists regardless of photoemission processes and depends, according to Richardson–Dushman law [7], on the type of material and temperature:

$$I_T = AT^2 \exp[-b/kT],$$

where A — material constant, b — work function.

It should be noted that the electric field formed by the positive bias voltage on the collector of photoelectrons affects the bending of energy zones at the interface „solid–vacuum“, increasing the number of electrons emitted.

Thus, the current recorded during the formation of the photocathode is represented as follows:

$$I_1 = I_{Reg} = I_F + I_T + I_L + I_{FI} + I_{IIF} + I_{IIT} + I_{In}. \quad (3)$$

2. Photoemission current detection method

Considering the structure of current detected during formation of the photocathode, it can be noted that:

— if the formed photocathode is not exposed to light, the detected current does not contain a component of the photoemission current, and only a part of the ionization current remains in the structure of the detected current, caused by shock ionization from the electrons of the thermionic process [8]:

$$I_2 = I_{Reg.d.} = I_T + I_L + I_{IIT} + I_{In}; \quad (4)$$

— when negative electrons are supplied to the collector relative to the photocathode, if the photocathode is exposed to light, apart from the induced currents, only insulator leakage current and ionization current component associated with photoionization will remain in the detected current :

$$I_3 = I_{Reg.neg.} = I_L + I_{FI} + I_{In}; \quad (5)$$

— when negative electrons are supplied to the collector and if the photocathode is not exposed to light, apart from the induced currents, only insulator leakage current will remain in the detected current :

$$I_4 = I_{Reg.d.neg} = I_L + I_{In}. \quad (6)$$

The conditions considered and the components of the current detected in these conditions are summarized in the following table.

By analyzing the table using formulae (3)–(6), we may obtain:

$$I_5 = I_1 - I_2 = I_{Reg} - I_{Reg.d.} = I_F + I_{FI} + I_{IIF}. \quad (7)$$

Photoionization current

$$I_6 = I_3 - I_4 = I_{Reg.neg.} - I_{Reg.d.neg.} = I_{FI}. \quad (8)$$

The sum of the photoemission current and the shock ionization current from photoelectrons can be obtained using formulae (7) and (8):

$$I_7 = I_5 - I_6 = I_1 - I_2 - I_3 + I_4 = I_F + I_{IIF}. \quad (9)$$

Structure of detected current under various detection conditions

Structure of the detected current		I_1	I_2	I_3	I_4
Mode singularities	Illumination	+	–	+	–
	Potential on the anode	+	+	–	–
True photocurrent	$f_2(U_a/L, P, S)$	+	–	–	–
Thermo-emission current	$AT^2 \exp[-b/kT]$	+	+	–	–
Leakage current	$f_3(U_a/R)$	+	+	+	+
Photoionization current	$f_4(E_{h\nu}, E_I, P_{Me})$	+	–	+	–
Shock ionization current from photoelectrons	$f_6(E_{eh\nu}, E_I, P_{Me})$	+	–	–	–
Shock ionization current from thermo-electrons	$f_7(E_{eT}, E_I, P_{Me})$	+	+	–	–
Induced current	I_{In}	+	+	+	+

Thus, by detecting the current in four different combinations of detection conditions, it is possible to obtain by elementary mathematical operations the sum of the photoemission current and the current generated from shock ionization of alkali metal molecules by photoelectrons.

Given that these currents have a relation

$$I_{IIF} = I_F \, \sigma \int_0^l (P_{AM}/kT)\, dl, \quad (10)$$

where P_{AM} — partial pressure of alkali metal, σ — coefficient allowing for the probability of alkali metal ionization, l — distance between the electrodes, we may obtain the formula (11) to define the true photocurrent:

$$I_F = I_7 \Bigg/ \left(1 + \sigma \int_0^l (P_{AM}/kT) dl\right). \quad (11)$$

If as partial pressure of alkali metals vapor we take maximum possible vapor pressure of cesium during formation $P_{Cs} = 1\,\text{Pa} = 10^{-2}\,\text{mbar}$, temperature $T = 473\,\text{K}$, maximum value of the cesium ionization section $\sigma_{Cs} = 10 \cdot 10^{-20}\,\text{m}^2$ [9] and distance between the anode and cathode in $l = 1\,\text{mm} = 10^{-3}\,\text{m}$, then the ratio of the shock ionization current and the photoemission current according to the formula (10) will be equal to

$$I_{IIF}/I_F = \int_0^l \sigma_{Cs} P_{AM}/kT\, dl$$

$$= \int_0^{10^{-3}} (10 \cdot 10^{-20} \cdot 1)/(1.38 \cdot 10^{-23} \cdot 473) dl = 0.016.$$

That is, the effect of shock ionization currents in devices with an interelectrode distance of less than 1 mm is insignificant and can be ignored. However, for $l \geq 40$ mm the relation $I_{IIF}/I_F \geq 0.6$ becomes significantly higher, and the effect of the shock ionization currents in this case shall be eliminated. The ways to eliminate the influence of shock ionization currents and their implementation will be considered in the next studies.

3. Implementation of the photoemission current detection method

To implement the detection method described above, a device has been developed, the scheme of which is shown in Fig.2.

The detection device is controlled by a microcontroller *1*, which sets the frequency of the photocathode polarity reversal *4*, changing the potential at the output of the power supply *2* due to the change rate of the control signal at the power supply input *2*, and controls the frequency of switching on/off the photocathode illumination by laser *3*, thereby ensuring synchronization of all combinations of illumination and polarity reversal of the photocathode power supply. The voltage drop occurring on resistor *5* as a result of the photocurrent flowing through it, is detected by the microcontroller after it is enhanced by the amplifier *6* and inverted by the inverter *7*, after which the microcontroller calculates the photoemission and thermal emission currents which go to the peripheral device *8* as a graph of changes in these values.

Changing the polarity of the photocathode's power supply leads to a change in the direction of current going through the resistor *5*, which is why the recorded signal is bipolar, so the measuring complex uses the inverter *7*, which transforms negative signal into a positive one and transmits the positive signal unchanged.

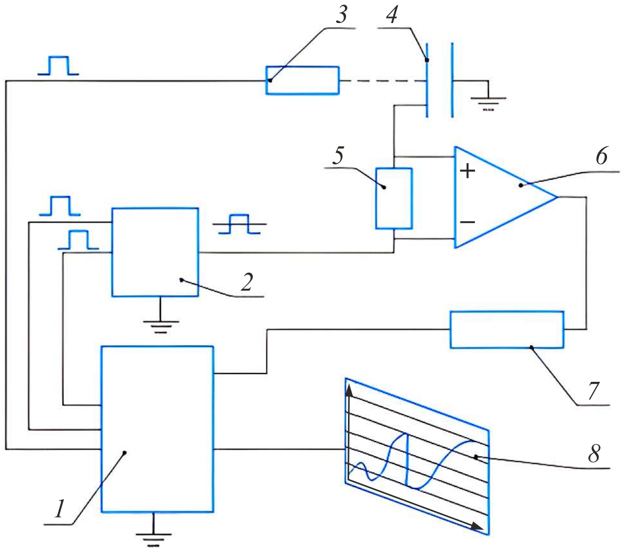

Figure 2. Measuring system: *1* — microcontroller, *2* — two-pole power supply, *3* — laser, *4* — photocathode, *5* — metering resistor, *6* — operating amplifier, *7* — inverter, *8* — recorder (display).

The recorded signal varies in the range from several hundred microvolts to tens of volts. It is impossible to detect such a large range directly, so the complex uses an amplifier *6* with a set of gain coefficients, allowing to cover the entire range of detected voltage.

A detailed description of the detecting device is given in paper [10].

4. Experimental procedure to check the method efficiency

To test the method efficiency, a series of processes were carried out for the formation of a bulky photocathode Cs_3Sb as part of commercial high-current photocell VD2000 (produced by FGUP „VNIIA“) for detection of the fast processes. The photocell is shown in Fig. 3.

Prior to the formation of the photocathode, an antimony film was deposited on a metal substrate, the thickness of which was controlled by the resistance of the witness and corresponded to the resistance of 10 Ω/square. The resulting antimony film was treated in cesium vapor at a temperature of 200 °C and the change in photocurrent was monitored in parallel using the developed detection method, where a laser with a wavelength of 405 nm was used as a light source to illuminate the photocathode. The photocathode was formed using the well-known technology [4], however, the process stopped at the peak of the true photoemission current, and not at the peak of the total signal.

The graph of pressure changes in the volume of the device and the signals detected during the entire process of photoemission layer formation is shown in Fig. 4.

At the beginning of the process, cesium was injected into the device, after which it was heated until a peak in photoemission current was reached. Upon reaching the

Figure 3. Photocell VD2000.

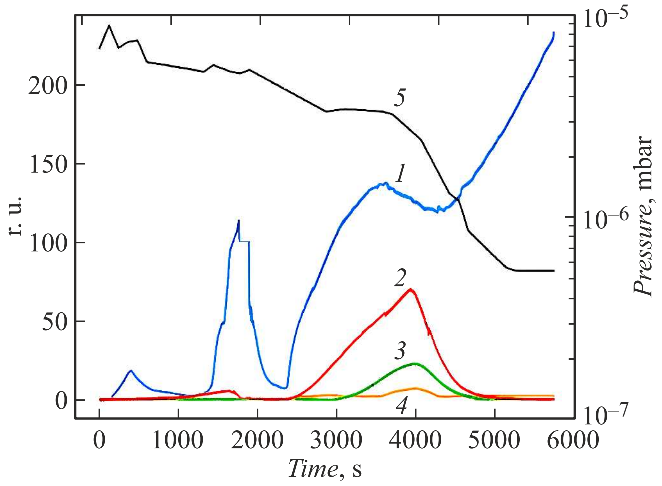

Figure 4. Graphs of changes in detected signals using the new detection method: *1* — photoemission current, ı2 — leakage current, *3* — thermal emission current and leakage current, *4* — photoionization current, *5* — pressure in the volume of the device.

maximum in 1500–2000 s, the heating stopped and the alkali metal source was soldered off, therefore, there is no data on the graph in this area. Next, the device was heated again until the peak of the photoemission current was reached, which was in the interval 3000–4000 s, after which the photocathode formation process stopped and the device cooled down under the furnace.

As can be seen from the curves, the drop in the photoemission current begins earlier than the moment when the leakage, ionization, and thermal emission currents decrease, i.e., the termination of the process at the peak of the total signal would lead to a significant decrease in the photoemission signal and, accordingly, to a decrease in the final sensitivity of the formed photoemission coating.

The average integral sensitivity of photocathodes formed using a technology where termination is accomplished through a drop in the total signal makes 33.37 μA/Lm, while the average integral sensitivity of the fabricated photocathodes upon termination of the formation process by a drop in the true photoemission current is 41.06 μA/Lm. At a wavelength of $\lambda = 410$ nm the quantum efficiency of the fabricated photocathodes makes $Y = 10.85 \cdot 10^{-2}$ electron/photon, and at a wavelength of $\lambda = 450$ nm $Y = 13.57 \cdot 10^{-2}$ electron/photon.

The normality of the obtained results distribution was checked according to the Pearson criterion.

The results obtained using standard method and results obtained using the new detection method were compared according to the Student's criterion, where the mathematical expectations of the two samples were compared.

$$H_0: \ \mu_1 = \mu_2; \quad H_1: \ \mu_1 \neq \mu_2.$$

The average sensitivity value, standard deviation, and the number of observations according to the standard detection method are equal to

$$\overline{X}_{st} = 33.37\,\mu\text{A/Lm},$$

$$\sigma_{st} = 9.24\,\mu\text{A/Lm},$$

$$n_{st} = 38.$$

The average sensitivity value, standard deviation, and the number of observations according to the proposed detection method are equal to

$$\overline{X} = 41.06\,\mu\text{A/Lm},$$

$$\sigma = 5.84\,\mu\text{A/Lm},$$

$$n = 16.$$

Critical value according to Student's statistics

$$t_{\text{cr}} = \frac{\overline{X} - \overline{X}_{st}}{\frac{\sigma^2}{n-1} + \frac{\sigma_{st}^2}{n_{st}-1}} = \frac{41.06 - 33.37}{\sqrt{\frac{5.84^2}{15} + \frac{9.24^2}{37}}} = 3.59.$$

p-value for t_{cr} with the number of degrees of freedom $N = \min(n-1, n_{st}-1)$

$$p - \text{value}(3.59; 15) = 0.003.$$

At the significance level of $\alpha = 0.05$, the hypothesis of mathematical expectations equality is denied, since $\alpha > p$-value; consequently, the second hypothesis is accepted that the mathematical expectation of experimental data obtained by the new method differs from the data obtained by conventional method, which confirms that control of the photocathode formation process by the new method has a clear benefit.

Conclusion

Thus, the newly developed method for detection of photoemission characteristics made it possible to isolate the photoemission component from the total signal recorded in standard photocathode formation processes, and made it possible to eliminate the problem of controlling changes in the photoemission current during formation of a bulky photocathode Cs_3Sb.

The photocathode formation process termination upon reaching the peak of the true photoemission current made it possible to increase the average integral sensitivity of the fabricated bulky photocathodes by 23,% and reduce the average square deviation of sensitivity by 1.5 times.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.V. Yupashevsky, A.V. Mironov, V.K. Makukha. *Avtomatizatsiya upravlenia protsessom formirovania multischelochnogo fotocatoda* (Novosibirsk, 2018), p. 4.

[2] A.V. Demidenko, N.A. Pkhaiko, A.I. Arefiev, A.G. Kazakov, Yu.L. Lyzhina. XII Intern.sicentific-technical conf. „Vacuum equipment, materials and technology" *Photocathode formation based on $SbCs_3$ by layer-by-layer deposition* (Moscow, Exhibition Center „Sokolniki", 2017, 11–13 th April), p. 4.

[3] M.N. Achasova, V.V. Anashina, A.V. Bozhenok, P.D. Vobly, V.B. Golubev, A.A. Zhukov, A.A. Korol, S.B. Oreshkin, E.E. Pyata, S.I. Serednyakov, Yu.A. Tikhonov, Yu.V. Usov, B.A. Schwartz. *Razrabotka vakuumnykh fotodiodov dlya scintillyatsionnykh kalorimetrov* (IYaF, Novosibirsk, 2005), p. 32.

[4] A. Sommer. *Fotoemissionniye materialy,* trans. from English Energiya, M., 1973 (Prinston, New Jersey, 1968)

[5] V.V. Balanyuk, I.A. Dubovoy, V.F. Krasnov, S.L. Musher, Yu.E. Nesterikhin, V.E. Ryabchenko, A.M. Prokhorov, V.K. Ushakov, M.Ya. Shchelev. ZhTF, **59** (1), 161 (1989) (in Russian).

[6] T. Reikhel, M. Iedlichka. *Fotoelectronniye katody,* transl.from Chech. V.N. Pshenisnova (Energiya, M., 1968), p. 160.

[7] N.A. Sobolev, A.G. Berkovsky, N.O. Chechik, R.E. Eliseev. *Fotoelektonniye pribory* (Nauka, M., 1965)

[8] P.I. Konovalov, D.G. Akopyan, R.I. Nurtdinov, O.A. Gerasimchuk. *Sposob registratsii fotoemissionnogo i termoemissionnogo tokov v protsesse formirovania fotoemissionnogo i/ili vtorichno-emissionnogo pokrytia* (Pat. 2807302 RU, MPK H01J 9/12, H01J 40/06, M., 2023), 19 p.

[9] A.P. Babichev, N.A. Babushkina, A.M. Bratkovsky and others rev.by I.S. Grigor'eva, K.Z. Mejlikhov *Fizicheskie velichiny, spravochnik.* (Energoatomizdat, M., 1991) 1232 p. (in Russian).

[10] P.I. Konovalov, D.G. Akopyan, R.I. Nurtdinov, D.V. Nikishin, O.A. Gerasimchuk. *Ustroistvo registratsii fotoemissionnogo i termoemissionnogo tokov v protsesse formirovania fotoemissionnogo i/ili vtorichno-emissionnogo pokrytia* (Pat. 221588 RU, MPC H01J 9/12, H01J 40/06, M., 2023), 11 p.

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