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Multi-channel vacuum-ultraviolet radiation detectors based on fiber-optical plates and phosphors

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Various modifications of vacuum-ultraviolet (VUV) radiation detectors were developed, which included open CCDs (charge-coupled devices) and CCDs with one and two fiber-optical plates. A layer of phosphor P-43 (Gd_2O_2S:Tb) was deposited to the outer surface of the detectors. The sensitive surface of such detectors can have a complex, including curly, shape. The spatial resolution was studied in the visible range of the spectrum, and the absolute sensitivity of the detectors was measured in the VUV region of the spectrum (wavelength range $\lambda = 4.9-13.5$ nm). The conditions of optimal use of detectors in VUV and X-ray spectrometers are considered.

Keywords: fiber optics, luminescent (phosphor) detectors, VUV and X-ray spectrometers.

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Research on design and application of various multichannel detectors, including CCD-based ones (CCD stands for „charge-coupled device"), has flourished in recent years. Of particular interest is the use of such detectors as real-time devices in vacuum ultraviolet (VUV) and X-ray spectrometers. Currently available CCD detectors may be divided tentatively into two groups: direct-imaging ones and those with backside illumination. The latter devices offer higher sensitivity within the VUV spectral range. Their main drawback is that they have a flat sensitive surface, which is unacceptable in certain cases (e. g., when spectra are recorded on complex focal surfaces: the Rowland circle in grazing incidence spectrometers or in crystal focusing spectrometers; see, e. g., [1]). So-called direct-imaging CCD detectors are more accessible and are significantly cheaper. However, owing to the presence of a technological layer on the surface, these detectors cannot be used directly to record VUV radiation, since this technological („dead") layer is highly absorbing. A phosphor layer, which transforms VUV radiation into visible one, is applied in order to prepare such detectors for use at VUV frequencies. The resulting visible radiation is recorded by a direct-imaging CCD detector (see, e. g., review [2]). Compared to the flat surface of a back-illuminated CCD, additional coupling of a CCD with fiber-optical plates provides an opportunity to produce a more complex (curved) configuration of the sensitive surface (cylindrical, spherical, etc.). Toward this end, various modifications of VUV radiation detectors based on direct-imaging CCDs, fiber-optical plates (FOPs), and phosphors were designed in the present study, and their characteristics were measured.

The designed detectors consist of three elements. Let us analyze the parameters of each of them. A Toshiba TCD 1304 linear CCD detector was used as a visible radiation detector. This detector is compact ($42 \times 10 \times 3$ mm) and has a large number of elements (3648 pixels) $6 \times 200\,\mu$m in size. The small period of the active part ($8\,\mu$m) provides for a potentially high spatial resolution. The detector offers high sensitivity in the visible region with a maximum at wavelength $\lambda = 550$ nm.

The chosen phosphor was finely dispersed P-43 (Gd_2O_2S:Tb) powder with average granule size $d \sim 3.0\,\mu$m. This phosphor has a high quantum yield in the VUV region of the spectrum with a maximum at a wavelength of 540 nm, which is well matched with the maximum sensitivity of the CCD detector. To maximize spatial resolution in the VUV region, the phosphor layer thickness was set to $\sim 10\,\mu$m.

Three basic modifications of detectors were used. The phosphor layer was applied directly to the sensitive elements of the CCD (the first modification, A), an FOP coupled to the CCD (the second modification, B), or an additional FOP coupled to the first FOP and the CCD (the third modification, C; see Fig. 1). This FOP may have a complex curved shape. These modifications allow one to detect radiation in both the VUV and X-ray spectral regions. The FOPs in all modifications had a fiber diameter of $6\,\mu$m. The plates were in optical contact with each other.

The spatial resolution of the detectors was measured using visible (green) light. This approach relies on the fact that VUV radiation is absorbed in a very narrow phosphor layer (with a phosphor granule size of $\sim 3\,\mu$m, it is absorbed completely in the very first layer). This layer emits visible luminescence (in the case of phosphor P-43, in the green region); radiation passes through the phosphor layer and is then recorded by the CCD detector. Thus, the spatial resolution may be investigated using visible radiation instead of VUV radiation, which simplifies significantly the measurement procedure. Measurements were performed with green light. The light source was an LED lamp

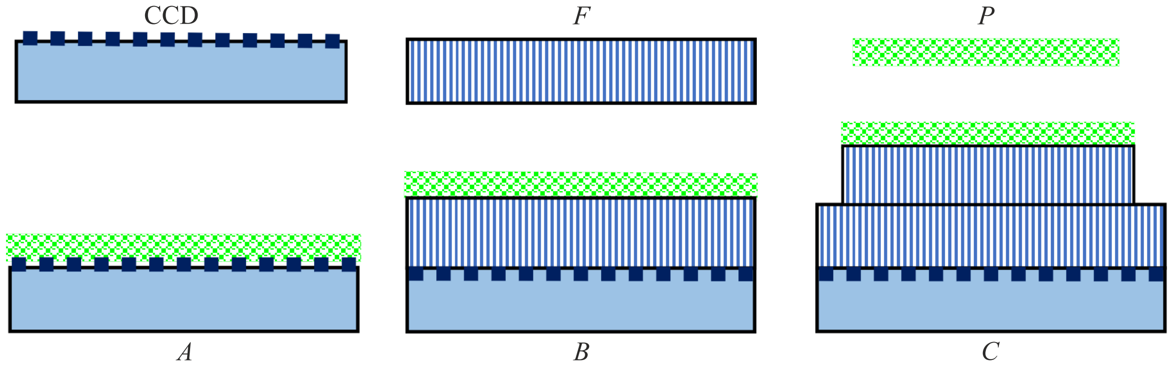

Figure 1. Basic modifications of the designed CCD detectors. A — CCD+phosphor layer; B — CCD+FOP+phosphor layer; C — CCD+FOP+FOP+phosphor layer. FOPs and phosphor layers are denoted as F and P, respectively.

that illuminated a UF-2 spectral slit. The slit image was transmitted by a microlens with a high reduction ratio to the detector input. When the slit image was transferred to the detector plane, its width was much smaller than a pixel, the FOP channel ($\sim 6\,\mu$m), or a phosphor granule ($\sim 3\,\mu$m); i. e., a δ function was effectively projected onto the detector under study. The measurement results are presented in Table 1.

Considering that the spatial resolution of the CCD detector without a phosphor layer is 2 pixels ($16\,\mu$m), we arrive at the following conclusions. The phosphor applied to the open CCD detector reduces its resolution by a factor of 1.5. The resolution decreases by a factor of 1.3 in switching from modification A to modifications B and C.

Absolute detector sensitivity calibration was carried out using an experimental setup based on a VUV radiation source, a monochromator, and a measurement chamber [3]. The radiation source was gas-filled capillary discharge plasma with the following parameters: main discharge capacitance, 20 nF; interelectrode voltage, 35 kV; current, 25 kA; pulse duration, 20 ns. A ceramic capillary 10 mm in length and 2 mm in diameter was filled with gas using an electromagnetic valve. Inert gases Ne, Ar, and Xe were used as the working gas at a pressure of 100–500 mTorr. The plasma electron temperature was $T_e \sim 60$ eV, which made it possible to excite spectra within the $\lambda = 4.9-13.5$ nm wavelength range (depending on the gas used). This radiation source was located at a distance of 50 mm from the entrance slit of a grazing incidence VUV monochromator with a constant angle of deviation (14°). Precision rotation of a spherical ($R = 1$ m) diffraction grating (600 lines/mm) was performed for wavelength scanning. A special two-channel chamber (Fig. 2) with a calibrated radiation detector and the detector under test was positioned at the monochromator output. The intensity of radiation passing through the exit slit was recorded by an absolutely calibrated AXUV-100 PIN diode. The tested detector was located nearby. Note that this calibration method does not depend on the reflection coefficient of the diffraction grating. The only important thing is that the illumination intensity along the vertical extent of the monochromator exit slit is the same in both channels. The equivalence of recording channels was verified at each wavelength used by rotating the test chamber by 180°.

The absolute sensitivity of detectors was measured at wavelengths as close as possible to those used in short-wave projection nanolithography applications (see, e. g., [4,5]). The following transitions were used for this purpose: $2p-3s$ in an Ar IX ion ($\lambda = 4.9$ nm); $2p-4d$, $4s$ in a Ne VIII ion ($\lambda = 7.4$ nm); $4d-4f$, $5f$ in a Xe XII ion ($\lambda = 10.8$ nm); and $4d-5p$ in a Xe XI ion ($\lambda = 13.5$ nm). The data from [6,7] were used to identify spectral transitions. Table 2 lists the measurement results.

The measurement error was determined by the scatter of experimental data and was found to be ~ 15 %. The relative values of sensitivity Y of different detector modifications „scale" well as $A : B : C = 1 : 9 : 33$. The dependence of Y on wavelength λ for all modifications takes the form of $Y \sim 1/\lambda \sim \hbar\omega$.

To conclude, we formulate certain guidelines for installing the designed detectors in spectrometers. It follows from Table 1 that the efficiency is maximized in modification A, when the phosphor layer is deposited directly onto the sensitive elements of the CCD detector. However, this modification has a flat sensitive surface. If the phosphor layer needs to be replaced often during operation (e. g., due to its damage or degradation under exposure to intense VUV radiation), it is recommended to use a modification of the CCD with one FOP onto which the phosphor layer is deposited (modification B). If necessary, one may remove this layer and apply another one. If the focal surface has a complex shape, the CCD modification with two FOPs

Table 1. Spatial resolution Δ (full width at half maximum) of various detector modifications (in pixels and μm)

Modification	Designation	Δ	
		pixel	μm
A	CCD+phosphor layer	3	24
B	CCD+FOP+phosphor layer	4	32
C	CCD+2 FOPs+phosphor layer	4	32

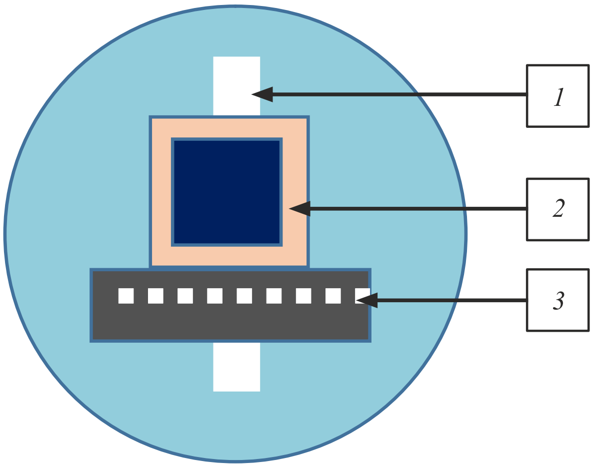

Figure 2. Test chamber at the output of the VUV monochromator with an absolutely calibrated AXUV-100 PIN diode and the tested detector. *1* — Exit slit, *2* — AXUV-100, and *3* — tested detector.

Table 2. Absolute sensitivity Y (photon/(count$\cdot\mu$m^2)) of different detector modifications

Wavelength λ, nm	Modification		
	A	*B*	*C*
4.9	0.002	0.018	0.067
7.4	0.003	0.026	0.092
10.8	0.0043	0.04	0.14
13.5	0.006	0.053	0.20

(modification C) is a better fit. The outer surface of the second FOP, onto which the phosphor layer is deposited, may have a complex shape (e.g., cylindrical or spherical shapes, including those with a small radius of curvature) in this case. This allows the focal surface of the spectrometer to be aligned with the sensitive layer of the detector, ensuring maximum spectral resolution. Detectors with a flat sensitive surface do not offer this option.

It follows from Table 2 that the coupling of CCDs with additional FOPs leads to a significant reduction in detector efficiency. This is especially true of modification C. However, the possibility of aligning the sensitive surface of detectors with the focal surface of spectrometers may provide a significant compensation for these losses. This is the novelty of this modification, which essentially represents a new class of detectors for application in VUV and X-ray spectrometers. The use of complex-shaped FOPs in such detectors was patented in Russia [8].

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Conflict of interest

The author declares that he has no conflict of interest.

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