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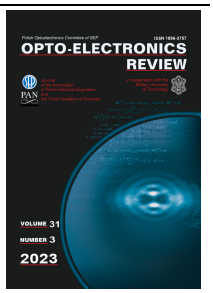

Review of X-ray detection systems

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Abstract

The article presents an overview and a classification of X-ray detection methods. The main motivation for its preparation was the need to select a suitable and useful method for detecting signals from a currently developed miniature micro-electro-mechanical system (MEMS) X-ray source. The described methods were divided into passive and active ones, among which can be distinguished: chemical, luminescent, thermo-luminescent, gas ionization, semiconductor, and calorimetric methods. The advantages and drawbacks of each method were underlined, as well as their usefulness for the characterisation of the miniature MEMS X-ray source.

1. Introduction

X-ray radiation is a form of electromagnetic radiation with short wavelengths (~1 pm to ~10 nm). Due to a different degree of permeability of this radiation depending on the type of material, it is widely used in many fields of analysis and research: medicine, industry, material research, and many others. This radiation can be used, for example, to test the correct assembly of electronic components on production lines, for imaging the human or animal body in medicine, or for material analyses [1, 2]. In addition, since the X-ray radiation is a type of ionizing radiation, it is used in medical therapies, e.g., in radiotherapy [3].

X-rays are generated usually by X-ray lamps [4] which differ in size (from 2 mm to few cm in length), energy (from several keV to few hundred keV), materials used for target and housing, type of electron emitter (thermal, field, or other), and mode of operation (reflective or transmission).

The authors are especially interested in miniaturization of X-ray sources. They are developing a micro-electro-mechanical system (MEMS) X-ray source made of silicon and glass that operates at low energies [5–7]. This X-ray source contains four electrodes: a cathode with a tip coated with carbon nanotubes, an extraction gate, a focusing electrode, and a target (Fig. 1). To ensure a consistently high vacuum in the structure, the ion-sorption micropump has been integrated into the X-ray source. The electrodes of the X-ray source and the pump are insulated by glass spacers with proper via holes. The various layers of silicon and glass are bonded together by anodic bonding to form a hermetically sealed vacuum enclosure.

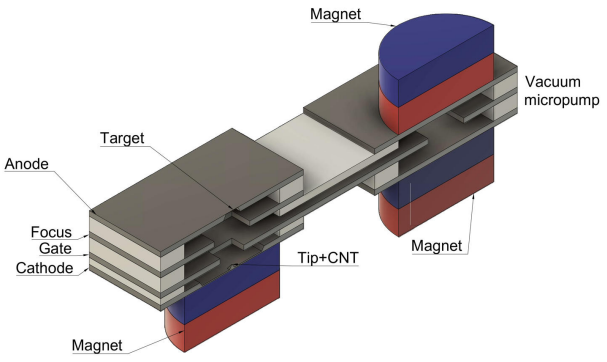

Fig. 1. Scheme of the MEMS X-ray source.

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The source operates in a transmission mode, electron beam is focused on the target and X-rays leave the source only through a small membrane made in its centre. It is intended that the source will generate low-energy X-rays ($E < 25$ keV, $I < 100$ μA) and the electron spot should be as small as possible. The small size of the source, operation at low radiation energies, and small focal spot are expected to enable unique applications, such as production of magnified images of small, e.g., biological objects or obtaining X-ray fluorescence (XRF) spectrograms.

Each X-ray system, except a source of radiation also requires a suitable detector, which can be used for characterising the source parameters at the development stage, or for imaging and other analysis – during exploitation. Thus, to be able to develop any new X-ray source, the first activity is to choose a proper detection method. In the case of this study, it is mostly necessary to assess the influence of different parameters of the source (its geometry, materials, and manufacturing techniques) on the intensity and shape of the X-ray beam, as well as its spectrum, and to optimize them at the development stage.

X-ray detectors are instruments used to measure and analyse spatial distribution, dose, energy, and other parameters of the radiation. These instruments should provide information of at least one of the following:

- presence of radiation,
- amount of radiation, relative or absolute, at a given moment,
- radiation energy.

There are different ways to classify X-ray detection methods and systems.

X-ray measurements can be performed both at a single spot and on a matrix. Point measurements are most often used to determine the value of the radiation in each area (dosimetric measurements) or detect its presence. Matrix measurements are performed as a compilation of many point measurements except that, unlike dosimetric measurements, it is not necessary to determine a specific parameter value, but they can be restricted only to relative values. However, some detectors allow to measure direct values in each point of the matrix.

Dosimetric measurements can be further classified according to the measured quantities:

- radiation dose measurement,
- measurement of radiation dose rate [5].

Detectors, considering the process of receiving information, can also be divided into passive and active detectors [3]. One of the first X-ray detectors were photographic plates. The use of photographic plates is a good passive method of obtaining qualitative information, but it is not suitable for quantitative measurements of, e.g., radiation intensity or spectral characteristics. Due to the need for quantitative information about X-rays, other types of X-ray detectors have been developed. Some of them are Geiger-Müller counter, proportional counter, scintillation counter, semiconductor detector, and many others.

The aim of this work is to review X-ray measurement methods and choose the best methods for applications in detecting signals from a miniature MEMS X-ray source. The sought detection system should ensure repeatability of measurement results, possibility of multiple usage, short time between successive measurements, ability to perform matrix measurements, and ability to detect X-rays with energies below 25 keV.

2. Passive detection

Passive detectors allow to obtain information about the radiation parameters affecting its active element. The received information concerning, e.g., radiation dose or spatial distribution of the beam requires additional processing. These detectors do not require power during measurement [3].

2.1. Chemical detectors

Ionizing radiation such as X-rays can initiate certain chemical reactions. Chemical detectors use some of these reactions to measure ionizing radiation. Constructions using such phenomena are, for example, the Fricke and Morse dosimeters whose operation is based on the oxidation of divalent iron to trivalent iron under the influence of ionizing radiation. With these dosimeters, the amount of iron produced by irradiation of an air-saturated iron sulphate solution is proportional to the radiation dose. As a result of chemical reactions involving water radiolysis products, Fe^{2+} ions are transformed into Fe^{3+}. The accumulation of Fe^{3+} ions causes intense light absorption with a wavelength of 307 nm. The dose of ionizing radiation is determined based on the absorption of visible light on a spectrophotometer. The typical reaction efficiency in this type of dosimeter is $G = (15.5 \pm 0.5)$ ions/100 eV. In another type of iron sulphate dosimeter, a solution of potassium thiocyanate is added to the irradiated active solution causing the whole mixture to turn red. The colour is due to the interaction of potassium thiocyanide with Fe^{3+} ions, formed because of the interaction of the active solution with ionizing radiation. The intensity of the colour is proportional to the concentration of Fe^{3+} ions, i.e., the dose of radiation. Detectors based on the cerium sulphate solution work in a similar way. Interaction with ionizing radiation of the tetravalent cerium ion causes its transformation into the trivalent state. This causes selective absorption of light in a 302 nm band which is manifested by colouration [8].

Another type of chemical detectors of ionizing radiation are detectors that measure the number of products of chemical reactions. Such detectors are based on, for example, carbon tetrachloride (CCl_4) or nitrous oxide (N_2O). Chemical detectors are used to measure large doses of ionizing radiation from sources with an activity of tens of curies (Ci). In the case of iron-sulphate detectors, they are used to measure radiation doses up to 500 Gy, while cerium-sulphate detectors measure radiation doses up to 10^4 Gy [8].

2.2. Photographic plates

Separate type of chemical detectors are photographic plates. These types of detectors are used to register the spatial distribution of the X-ray beam. The detection process is based on irradiating silver halide crystals contained in the emulsion that covers the film. As a result of X-ray irradiation, the silver halide particles are excited and remain in this state for an indefinite period. Grains

containing excited particles are converted by a chemical process into metallic silver, making the grain more visible. Visually, this is manifested by the blackening of this area. The emulsions used in photographic plates consist of a suspension of silver halide grains in an inert gelatine material. Photographic emulsions used for radiation detection fall into two main groups: radiographic films and nuclear emulsions. Nuclear emulsions are used to record the tracks of single charged particles, while radiographic films record the cumulative effect of many radiation interactions in a specific area in the form of this area darkening [9].

Chemical detectors, including photographic plates, are highly sensitive to X-rays, but the time from the measurement to obtaining output information is long. In addition, in the case of photographic films, further measurements are not possible since they are disposable. They are also sensitive to changes in external conditions, such as exposure to visible light which results in the problem of repeatability of measurements. These problems discredit chemical detectors for the reliable use in measuring signals from the X-ray source being developed.

2.3. Luminescent detection

Another type of X-ray measurements is detection using luminescence phenomena. They are based on the emission of light waves by active elements of the detectors as a result of the luminescent material excitation by a factor other than that causing only the thermal radiation emission. The phenomenon of luminescence can be directly used for the detection of ionizing radiation, e.g., in detectors using X-ray luminescence or radioluminescence where the phenomenon of luminescence is caused by the absorption of ionizing radiation. Luminescence can also be used as an indirect factor, e.g., in phosphor plates that absorb ionizing radiation and then emit visible light. The emission of light from the phosphor plate occurs as a result of photoluminescence. To cause this phenomenon, it is necessary to illuminate the phosphor plate with laser light after some prior exposure to ionizing radiation [10].

2.4. Detection using scintillators

The next type of X-ray detectors are scintillators. Scintillators are elements that, under the influence of ionizing radiation, emit electromagnetic radiation with a much longer wavelength, usually in the ultraviolet, visible, or infrared range. The passage of the molecule through the scintillation material causes the ionization process because of which its molecules and atoms are excited, and then, as a result of appropriate mechanisms dependent on the radiation energy, they emit light pulses. As a result of exposure to ionizing radiation, only part of the incoming energy causes scintillation, the rest is converted into thermal energy. The light emitted as a result of the scintillation phenomenon has a random direction which makes it necessary to use reflective layers that surround the scintillation material. In scintillators, doping of the scintillation material is often used to create additional energy levels. This results in a reduction in radiation absorption of the material generated by the scintillation which makes this material transparent to the radiation it emits [11].

The impact of X-ray or γ radiation on the scintillation material, depending on the energy, causes the occurrence of three mechanisms of electromagnetic interactions to varying degrees which are: photoabsorption, Compton scattering, and production of electron-positron pairs.

In the case of processing low-energy radiation (up to several hundred keV for heavy materials), photoabsorption is the dominant process. This mechanism involves the transfer of energy by the interacting photon to an electron from one of the electron shells of the absorber atom. The result is the creation of a photoelectron ejected with a kinetic energy equal to the energy of the incident photon minus the binding energy of the electron in its shell. Subsequently, the reorganization of the electron cloud causes the filling of electron gaps, resulting in the emission of Auger electrons. The highest probability of this process occurs when the energy of the initiating photon is comparable to that of the electron on one of the shells of the absorber atom.

Compton scattering is the dominant process when the radiation energy is greater than a few hundred keV. The probability of Compton scattering depends on the electron density in the scattering medium. The probability of this phenomenon increases linearly with the atomic number Z of the absorber material. This process is because the incident photon transfers only a part of its initial energy to an electron on one of the shells of the absorber atom and scatters at a certain angle θ with respect to the original direction. The electron ejected as a result of the photon interaction with an absorber atom is then absorbed by the scintillator, as a result of which energy is released according to (1)

$$E_e = E_\gamma - E'_\gamma - E_\mathrm{w}\,, \tag{1}$$

where E_γ – initial photon energy, E_w – electron binding energy, E'_γ – energy of the scattered photon (at electron rest mass of m_0) equals to (2)

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 \cdot c^2}(1 - \cos\theta)}\,. \tag{2}$$

The third mechanism that occurs in the scintillator is the production of electron (e^-) positron (e^+) pairs above the energy threshold of 1.02 MeV. This mechanism occurs mainly in the electric field of nuclei and to a lesser extent in the electric field of the electron cloud. The probability of this process, as in the case of photoabsorption and Compton scattering, is higher for materials with a high atomic number Z [11].

When the energy of the electron is high enough to reach the ionization threshold, free carriers are created which move randomly in the crystal until they encounter a defect through which they are trapped or recombine in the luminescent medium. If the ionization threshold is not reached, the electron and the hole release some of their energy as a result of coupling with lattice vibration modes, until the top of the valence band for the hole and the bottom of the conduction band for the electron are reached.

For a material to be a scintillator, it must contain luminescent centres. These are external ions, which are usually dopants or internal ions in the form of a molecular

lattice system, or its defects in which there is a radiative transition between an excited state and a lower energy state. In the scintillator, to avoid re-absorption of the emitted light, it is necessary that the energy levels involved in the radiation transition are lower than the band gap [11].

In the scintillation detection, the detectors efficiency is highly dependent on geometric dimensions of the scintillator. A larger input surface of the scintillator makes it possible to absorb more photons of ionizing radiation. The photons absorption by the scintillator is also affected by its thickness and photon energy. Higher photon energy typically results in the need for thicker scintillators to achieve the same efficiency. Scintillation detectors are perfect for direct observation of radiation from small sources of ionizing radiation [11].

Both scintillators are commercially available in various forms such as, e.g., powder, foil which allows for their easy adaptation to complex shapes. This is a significant convenience when integrating with a small X-ray source, e.g., by placing a detection element closely above the source. The ease of shaping these elements and combining them with the developed source significantly extends its future applications. In addition, luminophore and scintillators allow for matrix measurement. Depending on the type of luminophore or scintillator, the luminescence decay time may be low enough to make X-ray films. Numerous advantages of these elements make them a candidate for use in the detection of radiation from a miniature MEMS X-ray source.

2.5. Radioluminescent fiber optic sensors

Radioluminescent fibre optic sensors are another type of detectors capable of recording X-rays. They are typically used to detect high-energy radiation and allow real-time monitoring of the radiation beam. Thanks to them it is possible to determine both the dose of radiation, its intensity, and the spatial distribution of the beam in the case of using a matrix of many optical fibres. These sensors have a high radiation durability due to the use of silica optical fibres. The fibres are properly doped with rare earth elements, thus they can be adapted to the specific energy range of ionizing radiation. The radioluminescent optical fibre sensor consists of: small radioluminescent scintillator, optical fibre, and optical detector (e.g., photomultiplier, photodiodes).

In these detectors, the problem is the effect of false luminescence which arises as a result of radiation affecting the optical fibre. This makes it necessary to cut off this signal from the signal coming from the scintillator to avoid a drastic deterioration of the detector properties. False luminescence can be generated in an optical fibre due to the phenomena of fluorescence, phosphorescence, and the Cherenkov phenomenon. The fluorescence in the optical fibre arises due to the intrinsic scintillation properties of the optical fibre material. There are several solutions to distinguish a signal coming from radioluminescence in the scintillator from a false one. One of them is to use the same optical fibre in parallel as a reference, only without the scintillator, and then subtract the signals generated by the two optical fibres. This solution is effective but increases the physical size of the detector and reduces its spatial resolution [12].

These detectors have slight disturbances of the intercepted radiation which allows for both precise determination of the radiation dose value at each point and good spatial resolution of the measurement. In addition, they are characterised by high sensitivity and repeatability of measurement, insensitivity to environmental conditions, high radiation stability and non-toxicity which is particularly important in medical applications [12].

Radioluminescent fibre optic sensors can perform repeatable and precise measurements with good spatial resolution, however, majority of available products do not allow the detection of X-rays with low energies below 25 keV which makes it harder to use them to detect signals from the X-ray source being developed.

2.6. Phosphor plate radiography

The radiography of phosphor plate (PSP) uses the phenomenon of photostimulated luminescence (PSL) and allows to obtain an image of the spatial distribution of the radiation beam. The PSP is a memory plate which means that the image is not obtained immediately after exposure to X-rays but only after irradiation with electromagnetic radiation in the range of visible light of appropriate power. The PSP consists of three basic layers: the carrier substrate, the photostimulated phosphor layer, and the protective layer [13].

The operation of the PSP is based on the stable energy changes of atoms caused by the interaction of X-rays which results in the formation of a latent image. These changes are proportional to the number of interacting X-ray photons. Obtaining a visible image from a latent image causes the phenomenon of photoluminescence. The PSP board is illuminated with a beam of light from a laser of appropriate power. This causes excitation of atoms which results in a further stage in a return to the ground state and emission of visible light. Its intensity is proportional to the intensity of radiation with which the plate was illuminated. The emitted visible light can be recorded by a visible light detector, e.g., a CCD matrix [13].

Due to the long time between the measurement and its reading, the method based on PSP radiography is not suitable for useful measurements of signals from a miniature X-ray source.

2.7. Thermoluminescent detectors

Another type of detectors based on luminescence phenomena are thermoluminescent detectors (TLDs). The principle of operation of these detectors is based on the emission of visible light by an active substance caused by its heating resulting from the absorption of the radiation dose. The intensity of the emitted visible light is proportional to the dose of radiation dose. The active substance in these detectors is a thermoluminescent luminophore, mainly a dielectric material, with defects in the crystallographic lattice. They act as traps or metastable energy levels. To prevent electrons from moving between the traps, defects are spaced sufficiently far from each other. When the active substance is exposed to radiation, some of electrons are trapped as a result of which they are transferred to a metastable energy level. Then, because of heating, the electrons get out of the traps to a higher energy

level and then return to the ground state, resulting in the emission of visible light photons. After the heating process, the TLDs can be reused [1]. The process of changes that occurs in the thermoluminophore as a result of interaction with ionizing radiation is shown in Fig. 2.

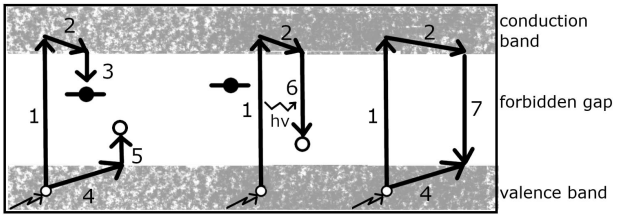

Fig. 2. The process of changes in the electron configuration of a thermoluminophore under the influence of exposure to ionizing radiation.

Subsequent changes in the electron configuration are marked in Fig. 2 as:

1. Transition of the electron to the conduction band as a result of the energy supplied from ionizing radiation.
2. Electron movement in the conduction band.
3. Electron trapping.
4. Displacement of the hole created as a result of the ejection of an electron by ionizing particle.
5. Recombination of the hole with the electron coming from the luminescence centre.
6. Recombination of the electron with the luminescence centre causing the emission of light which occurs during irradiation of the crystal.
7. Recombination of an electron with a hole in the valence band which does not lead to luminescence [14].

In TLDs, light intensity is measured as a function of temperature using a photomultiplier system and a counting system. The photomultiplier is an element that converts electromagnetic radiation into current pulses and amplifies them. The resulting current pulses are then counted by the counting system. The data obtained provide information on the dose of radiation absorbed by the active element in each period [1].

TLDs, despite their high sensitivity, do not fulfil all the requirements for application in a miniature X-ray source because of the need of using photomultipliers whose geometric dimensions significantly limit the possibility of combining these detectors into measurement matrices.

2.8. Porous dielectric detectors

Another type of X-ray detector are dielectric detectors. One of them is a porous dielectric detector (PDD). PDDs are elements allowing to determine the dose of radiation affecting the active element. The operation of this type of detectors is based on electrical discharge machines (EDM) mechanism occurring in porous dielectrics. As active materials, porous dielectrics, such as CsI, CsBr, KCl, KBr, Na3AlF6, MgO are the most often used. In the active material, electrons and holes are generated in the pore walls under the influence of ionizing radiation. When the energy of the generated electrons is high enough, secondary electrons and holes can also be produced creating successive electron-hole pairs. An electric field is applied to the active layer which accelerates the secondary electrons in the pores. This process works in an avalanche when the electron emission coefficient $G > 1$ because of which accelerated electrons produce more secondary electrons and holes on the surfaces of the pore walls (Fig. 3). For PDD to work stably and have good spatial resolution, it is necessary to provide vacuum conditions, with a vacuum better than $7 \cdot 10^{-3}$ Tor. The advantage of these detectors is their very good time resolution [15].

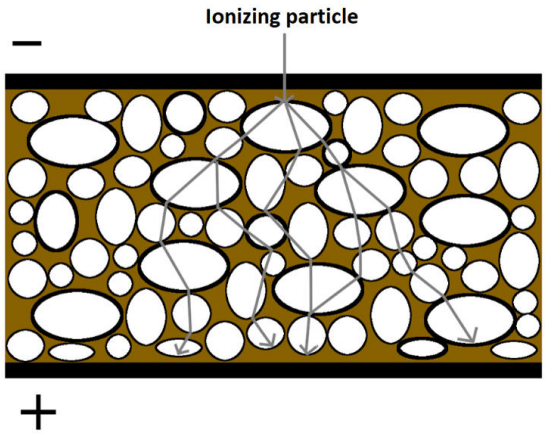

Fig. 3. Schematic view of drift and multiplication by ionization of electrons in porous dielectrics under the action of an external electric field. (based on Ref. 15).

With their construction considered, PDDs can be divided into multiwire and microstrip detectors. Multiwire porous detectors consist of an anode in the form of wires, a cathode, and a porous dielectric material between them (Fig. 4).

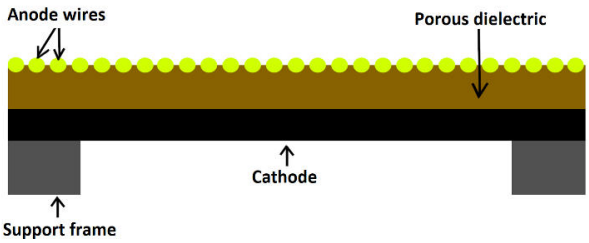

Fig. 4. Schematic view of a multiwire PDD. (based on Ref. 15).

The microstrip detector is made of an insulating plate covered with metal strips, a microgrid anode, and a porous dielectric material between them (Fig. 5) [15].

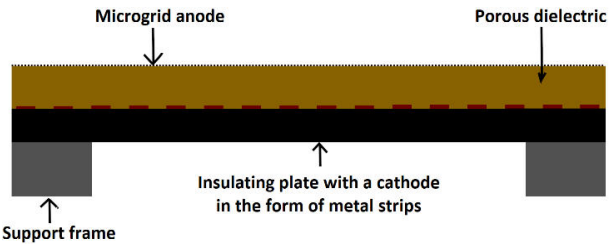

Fig. 5. Schematic view of a microstrip PDD. (based on Ref. 15).

Dielectric detectors are mainly intended for the detection of hard X-rays; therefore, they cannot be used in conjunction with the developed X-ray source.

3. Active detection

Active detectors provide information about the impact of the ionizing radiation beam on its active element. This information appears in the form of an electrical impulse in real time. These detectors require power during measurement. These detectors include scintillation counters, gas detectors, semiconductor detectors, and calorimetric detectors [3].

3.1. Gaseous ionization detector

Gaseous ionization detectors are constructed of a tank with a special gas and electrodes to which a high voltage is connected. The irradiated gas is ionized and the electric field causes it to drift and, as a result, an electrical impulse is generated.

One of the gas detectors is the Geiger-Müller counter. It is a counter of ionizing radiation that allows to determine the dose of this radiation, but without the possibility of the selective measurement of its type and without the possibility of measuring radiation intensity. The basic element of this device is a Geiger-Müller tube which is constructed in the form of a simple gas lamp containing two electrodes. The outer housing in the form of a hermetic cylindrical tube made of metal or glass with a conductive layer sputtered onto it is a cathode in this case. On the other hand, it is made as a thin tungsten wire placed inside the housing. Inside the housing, there is argon with the addition of alcohol vapour.

The operation of this counter is based on the phenomenon of ionization of the gas trapped inside the tube under the influence of ionizing radiation and the acceleration of molecules in the electric field generated by the applied high voltage (~400 V). The ionization of argon causes the detachment of negatively charged electrons from its atoms which results in the formation of positive argon ions (Ar^+). Positive argon ions and detached electrons are accelerated in the electric field. Argon ions go to the walls of the tube, which is the cathode, and electrons go towards the anode. Accelerated argon ions heading towards the cathode often collide with other non-ionized argon atoms, leading to their further ionization, therefore this process leads to an avalanche discharge. The excitation of argon atoms also causes the emission of ultraviolet radiation which intensifies the effect of knocking electrons out. Avalanche discharge is manifested by a temporary current flow between the cathode and the anode which in a closed circuit with a resistor causes a voltage drop. The registration of such a pulse allows to conclude that ionizing radiation has just penetrated the tube. The Geiger-Müller counter allows to count pulses but it is necessary that the voltage returns to the level from before the discharge; otherwise, it would be impossible to count subsequent pulses. Due to the need for the voltage to return to its original state, there is a certain time during which the radiation cannot be registered. Reducing this time is achieved by adding alcohol vapours, i.e., polyatomic molecules, to argon which usually fill about 10% of the total volume. Polyatomic particles absorb ultraviolet radiation and prevent electron ejection from the cathode which extinguishes the discharge [16].

Gas detectors are used for spot measurements. Due to their large dimensions compared to those of the miniature X-ray source and their inability to perform matrix measurements, they do not meet the requirements for the sought-after detection system.

3.2. Calorimetric detectors (calorimeters)

Calorimeters are detectors of ionizing radiation; their operation is based on a thermodynamic transformation. Their operation mechanism is based on the measurement of thermal energy generated as a result of exposure to ionizing radiation. The energy of ionizing radiation absorbed by the active material of the detector is converted into heat which increases the temperature in the absorbing medium of the detector.

These detectors are mainly intended for recording large doses of radiation due to small changes in temperature caused by radiation absorption. In calorimeters, the active material must have the lowest possible heat capacity to achieve the largest temperature changes caused by exposure to radiation. Calorimeters are characterised by a high accuracy of measurement of the absorbed dose with a measurement uncertainty < 1%.

There are many types of calorimeter designs but each one consists of two main elements which are the active medium made of a material that absorbs and converts ionizing radiation into heat and a temperature sensor [17].

In the past, calorimeters were manufactured as large devices, e.g., water calorimeters [3] but today they are increasingly manufactured in the form of chips. Miniaturized calorimeters with absorbers only a few mm thick are now widely used and many studies are being conducted on their new designs [18–20]. Such chip calorimeters allow the creation of 2D and 3D detector arrays allowing the measurement of spatial variability of radiation [21]. Miniature calorimeters are currently manufactured, for example, as a combination of a thermistor in the form of a thin layer of vanadium oxide and an absorber in the form of a microstructure of SU-8 resin. This type of detector is perfect for X-ray detection [22].

3.3. Semiconductor detectors

The next type of active X-ray detectors are semiconductor detectors. They use the phenomenon of ionization in a solid-state materials. They are used mainly to detect X-rays and γ radiation. These detectors determine the dose and intensity of radiation. Due to their small geometrical dimensions, they can also be used in the form of sensor matrices making it possible to determine the spatial distribution of the radiation beam. The basic element of these detectors is a reverse-biased *p-n* semiconductor diode. In the normal state, the diode does not conduct electricity but, as a result of exposure to ionizing radiation, enters the active region. Under the influence of ionizing radiation, electron-hole pairs are generated which are attracted by the electrodes which results in the appearance of an electrical impulse. The operation of these detectors is like the attraction of electron-ion pairs by the electrodes in the ionization chamber. Semiconductor detectors are much more sensitive than gas detectors because the energy

needed to create electron-hole pairs in a semiconductor (3.7 eV for silicon and 2.8 eV for germanium [23]) is on average about ten times less than the energy needed to ionize an atom in gas [9]. This means that in a semiconductor, a molecule of a given energy will produce on average about ten times more current carriers than in a gas. As a result, semiconductor detectors have a very good energy resolution. Semiconductor detectors are additionally often cooled with liquid nitrogen. This is to improve their energy resolution, due to the reduction of the semiconductor resistance when the temperature drops [5].

Semiconductor detectors provide good measurement resolution, enabling matrix measurements and dosimetric measurements of radiation energy which makes them a good solution for measuring radiation from a miniature MEMS X-ray source. However, choosing an optimal semiconductor detector from commercially available solutions is not that easy. X-ray cameras used most frequently for medical imaging are dedicated to high-energy radiation and often do not allow adjustment of any acquisition parameters [24]. Semiconductor spectrometers based on silicon drift detectors (SDDs) allow to determine the energy of X-ray radiation with a very good resolution (electronic impulses are proportional to photon energy) [25]. However, they are very sophisticated instruments requiring cooling and vacuum packaging which leads to the fact that only spot measurements are possible.

An example of a semiconductor detector that allows for measuring both spatial distribution and energy is the MiniPIX TPX3 camera from Advacam [26]. This camera captures the spectrum of the measured X-rays in each pixel. Thanks to the ability to measure energy, position, and time, the device can digitally record traces of interacting ionizing particles. The minimum energy detected by this camera is 3 keV (for Si sensor active material) and 5 keV (for CdTe active material); however, the energy resolution is 0.5–1 keV for Si and 1.1–3.6 keV for CdTe which is much worse than for SDDs. The biggest advantage is that the camera enables recording the image with a resolution of 256×256 pixels. This apparatus is ideal for initial characterisation of the developed X-ray source. Although it does not ensure as good spatial resolution as scintillator detectors and as good energetic resolution as SDDs, it is a good compromise solution.

3.4. Scintillation detectors and counters

The scintillation detector consists of the previously described scintillator and a detection system in the form of, for example, photomultiplier, photodiode, avalanche photodiode, or CCD matrix. The scintillator itself is a passive element but in combination with other elements processing and amplifying its signal, it is an active detector. One of the most frequently used detectors in combination with a scintillator is a photomultiplier. Photomultipliers are usually cylindrical in shape, several cm long and several in diameter. The photomultiplier in its construction has a window on one of the walls covered with a thin material that forms a photocathode. As a result of exposure of the photocathode to electromagnetic radiation, electrons are emitted as a result of the photoelectric effect. The number of electrons ejected is proportional to the number of scintillations in the scintillator. The ejected electrons provide only a small impulse that is impossible to observe directly; therefore, it is necessary to amplify it. The pulse amplification mechanism is implemented by dynodes powered by high voltage from a voltage divider, ensuring a constant potential difference between successive dynodes. The ejected electrons are accelerated in the electric field between the series of dynodes. The accelerated electrons knock out more electrons from dynodes. This causes an increase in the number of electrons that go to the anode and, as a result, give a measurable electrical impulse. Despite the amplification of the pulse by dynodes, the current is still small, therefore, it is necessary to use preamplifiers and linear amplifiers (Fig. 6) [9].

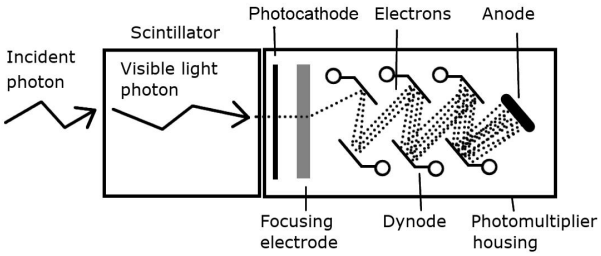

Fig. 6. Schematic appearance of a scintillation counter. (based on Ref. 27).

Combining a scintillator with a photomultiplier is used to determine the total value of the absorbed radiation dose. An array measurement is required to register the resulting X-ray image. For this purpose, in conjunction with the scintillator, matrix detectors are used, e.g., CCD or CMOS matrices which record the light emitted by the scintillator [27]. In this case, the spatial resolution can be very high. It depends only on the scintillator grain size (can be nanometric) and the applied visible light camera which are currently very well developed.

4. Detection of signals from a miniature MEMS X-ray source

The miniature source of MEMS X-ray radiation developed in our group, in its concept, allows the generation of a point beam of low-energy X-rays. One of the potential applications of this source is the imaging of small objects, e.g., biological ones. The other is the XRF system. Due to the small dimensions of the source, a reasonable solution to detect its signals is to use small detection elements that can be placed within a short distance from it. Due to both, the future applications and the current need to optimize the elements of the source and characterise the generated beam, two types of detectors chosen from all presented in this article seem to be most appropriate.

5. Conclusions

The first solution suitable for intensity and spatial distribution measurements consists of combining a luminophore or scintillator in the form of a pressed powder applied to a carrier surface, e.g., foil, with a visible-light detector, e.g., in the form of a CCD or CMOS camera. This solution will provide the possibility of studying the influence of X-ray source parameters on the parameters of

the received X-ray beam, such as the relative value of radiation intensity, spot width, and shape. In addition, this solution can be used for X-ray imaging of objects. The other instrument, which enables the measurement of energetic distribution, is a semiconductor SDD detector. It allows to acquire the spectrum of X-ray radiation which can be especially important when choosing proper target material and adjusting electron beam energy. Moreover, it can be used together with the MEMS X-ray source to form a complete miniature XRF system. As mentioned previously, a compromise solution which allows for both spatial and energy-dependent measurements is Advacam camera, but in that case both parameters will have limited resolution.

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References

[1] Swiątek, Z. & Fodchuk, I. X-Ray topography of the subsurface crystal layers in the skew asymmetric reflection geometry. *Arch. Metall. Mater*. **61**, 1931–1938 (2016). https://doi.org/10.1515/amm-2016-0310

[2] Mackiewicz, P. & Szydło, A. Application of X-ray tomography to assess fatigue structural changes in asphalt mixtures. *Bull. Pol. Acad. Sci. Tech.* **67**, 307–315 (2019). https://doi.org/10.24425/bpas.2019.128604

[3] Stark, G. X-ray Definition, History & Facts. *Encyclopedia Britannica* (2023). https://www.britannica.com/science/X-ray

[4] Behling, M. *Diagnostic, X-Ray Sources, Technology, Manufacturing, Reliability*. (Boca Raton, Taylor and Francis, CRC Press, 2015).

[5] Górecka-Drzazga, A. Miniaturowe źródła promieniowania rentgenowskiego. *Prz. Elektrotechniczny* **90**, 108–112 (2014). (in Polish) https://doi.org/10.12915/PE.2014.11.30

[6] Grzebyk, T., Turczyk, K., Górecka-Drzazga, A. & Dziuban, J. A. Towards a MEMS Transmission Point X-ray Source. in *34th International Vacuum Nanoelectronics Conference (IVNC)* 1–2 (IEEE, 2021). https://doi.org/10.1109/IVNC52431.2021.9600697

[7] Urbanski, P., Bialas, M., Krysztof, M. & Grzebyk, T. Mems X-Ray Source: Electron-Radiation Conversion. in *21st International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS*) 42–45 (IEEE, 2022). https://doi.org/10.1109/powermems56853.2022.10007561

[8] Borrely, S. I., Duarte, C. L. & Sampa, M. H. O. Ionizing Radiation As A Tool For Detoxification of Whole Effluents. in *Recent Advances in Multidisciplinary Applied Physics* (ed. Méndez-Vilas, A.) 259–264 (Elsevier, 2007). https://doi.org/10.1016/B978-008044648-6.50042-2

[9] Knoll, G. F. *Radiation Detection and Measurement*. (John Wiley & Sons, 2010).

[10] Cebim, M. A., Oliveira, H. H. S., Krauser, M. O. & Davolos, M. R. X-Ray-Excited Optical Luminescence. in *Recent Advances in Complex Functional Materials* (eds. Longo, E. & de Almeida La Porta, F.) 177–193 (Springer International Publishing, 2017). https://doi.org/10.1007/978-3-319-53898-3_7

[11] Lecoq, P. Scintillation Detectors for Charged Particles and Photons. in *Particle Physics Reference Library Vol. 2*, *Detectors for Particles and Radiation* (eds. Fabjan, C. W. & Schopper, H.) 45–89 (Springer International Publishing, 2020). https://doi.org/10.1007/978-3-030-35318-6_3

[12] Veronese, I. *et al*. Radioluminescence dosimetry by scintillating fiber optics: the open challenges. *Proc. SPIE* **8852**, 88521L (2013). https://doi.org/10.1117/12.2027041

[13] Sampaio-Oliveira, M. *et al*. How does ambient light affect the image quality of phosphor plate digital radiography? A quantitative analysis using contemporary digital radiographic systems. *Sensors* **22**, 8627 (2022). https://doi.org/10.3390/s22228627

[14] Niewiadomski, T. Dozymetria Termoluminescencyjna w Praktyce. (Instytut Fizyki Jądrowej im. Henryka Niewodniczańskiego, 1991). (in Polish)

[15] Wiedemann, H. *Advanced Radiation Sources and Applications*. (Springer Science & Business Media, 2004).

[16] Bartuś, T. *Licznik Geigera-Müllera – Zasada Dzialania.* (2022). http://home.agh.edu.pl/~bartus/index.php?action=efekty&subaction=arduino&item=30 (in Polish)

[17] Fabjan, C. W. & Fournier, D. Calorimetry. in *Particle Physics Reference Library Vol. 2*, *Detectors for Particles and Radiation* (eds. Fabjan, C. W. & Schopper, H.) 201–280 (Springer International Publishing, 2020). https://doi.org/10.1007/978-3-030-35318-6_6

[18] Khaw, M. K., Mohd-Yasin, F. & Nguyen, N. T. Microcalorimeter: Design considerations, materials and examples. *Microelectron. Eng.* **158**, 107–117 (2016). https://doi.org/10.1016/j.mee.2016.03.050

[19] Koh, L., Lee, W. & Shin, J. H. High-sensitivity chip calorimeter platform for sub-nano watt thermal measurement. *Sens. Actuator A Phys.* **241**, 60–65 (2016). https://doi.org/10.1016/j.sna.2016.02.001

[20] Feng, J., Svatoš, V., Liu, X., Chang, H. & Neužil, P. High-performance microcalorimeters: Design, applications and future development. *Trac-Trends Anal. Chem.* **109**, 43–49 (2018). https://doi.org/10.1016/j.trac.2018.09.017

[21] Torres, F. E. *et al*. Enthalpy arrays. *Proc. Natl. Acad. Sci. U.S.A.* **101**, 9517–9522 (2004). https://doi.org/10.1073/pnas.0403573101

[22] Kim, J. *et al*. Development and application of chip calorimeter as an X-ray detector. *Curr. Appl. Phys.* **20**, 337–343 (2020). https://doi.org/10.1016/j.cap.2019.11.020

[23] Bilski, P. *Detekcja i Detektory Promieniowana Gamma oraz Pomiary Energii Fotonów*. (2022). (in Polish) http://www.if.pw.edu.pl/~pluta/pl/dyd/mfj/zal03/bilski/index.html

[24] REMEDI Revolution in Medical Device. *Portable X-Ray Digital Camera.* (2023). https://remedihc.com/product-portable-x-ray/

[25] KETEK GmbH. *Silicon Drift Detectors (SDD) – KETEK GmbH.* (2023). https://www.ketek.net/sdd/

[26] ADVACAM *MiniPIX TPX3 X-ray diffraction camera for Non-Destructive-Testing*. (2023). https://advacam.com/camera/minipix-tpx3

[27] Kisiel, A. *Scyntylatory.* (2022). (in Polish) https://docplayer.pl/206781397-Scyntylatory-a-kisiel-scyntylatory.html