Pure & Appl. Chem., Vol. 67, No. 10, pp. 1745–1760, 1995.
Printed in Great Britain.

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

ANALYTICAL CHEMISTRY DIVISION
COMMISSION ON SPECTROCHEMICAL AND OTHER OPTICAL PROCEDURES FOR ANALYSIS*

Nomenclature, Symbols, Units and their Usage in Spectrochemical Analysis—XI

DETECTION OF RADIATION

(IUPAC Recommendations 1995)

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CONTENTS

Nomenclature, symbols, units and their usage in spectrochemical analysis—XI. Detection of radiation (IUPAC Recommendations 1995)

SYNOPSIS

This report is 11th in the series on Spectrochemical Methods of Analysis issued by IUPAC Commission V.4. It is concerned with Radiation Detection as used in analytical atomic and molecular emission, absorption, and fluorescence spectroscopy in the X-ray and optical wavelength region (i.e. from 10 pm to 1 mm). The present report has five main sections: terms relating to (a) fundamental properties of detectors, (b) thermal detectors ,(c) photo-emissive detectors, (d) semiconductor detectors, and (e) spatially resolving detectors.

Although still of considerable importance, photographic emulsions are not included..

1 INTRODUCTION

A series of documents dealing with nomenclature, symbols and units used in spectrochemical analysis is issued by IUPAC:

Part I [Pure Appl. Chem. 30, 653-679 (1972)] is concerned mainly with general recommendations in the field of emission spectrochemical analysis.

Part II [Pure Appl. Chem. 45, 99-103 (1976)] gives some basic rules on data interpretation.

Part III [Pure Appl. Chem. 45, 105-123 (1976)] deals extensively with the nomenclature of analytical flame (atomic emission and absorption) spectroscopy and associated procedures.

Part IV [Pure Appl. Chem. 52, 2541-2552 (1980)] concerns X-ray emission (and fluorescence) spectroscopy.

Part V [Pure Appl. Chem. 57, 1453-1490 (1985)] deals with the classification and description of radiation sources.

Part VI [Pure Appl. Chem. 56, 231-345 (1984)] covers molecular luminescence spectroscopy.

Part VII [Pure Appl. Chem. 60, 1449-1460 (1988)] is concerned with molecular absorption spectroscopy (UV/VIS).

Part VIII [Pure Appl. Chem. 63, 735-746 (1991)] deals with a new nomenclature system for X-ray spectroscopy.

Part IX [Pure Appl. Chem. (1995)] covers fundamental aspects of spectral dispersion and isolation of radiation.

Part X [Pure Appl. Chem. 60, 1461-1472 (1988)] deals with sample preparation for analytical atomic spectroscopy and other related techniques.

This document, part XI, deals with the detection of radiation. It complements parts I, III, VI, VII, and IX of the series. Basic aspects of radiation detection, as well as all radiation detectors of practical importance, with the exception of photographic emulsions, as used in analytical atomic and molecular spectroscopy are covered. The spectral region ranges from 10 pm to 1 mm. Wherever wavelength is mentioned, wavenumber or frequency or, in the case of X-rays, energy may be used. In some cases detectors for X-rays, which are generally based on the effect of X-rays on the electronic structure of matter, are treated separately.

The most common detectors are

- photomultiplier tubes
- scintillation counters
- gas-filled detectors
- semiconductor detectors.
- (- photographic emulsions)

In addition, the following spatially resolving detectors are of considerable interest

- vidicons
- photodiode arrays
- charge-transfer devices
- multichannel plate photomultipliers
- spatially resolving proportional counters

This document does not deal with any associated electronics.

2 GENERAL PROPERTIES

The *radiation input*, i.e. the quantity to be measured by a *radiation detector* may be *radiant power* Φ, *irradiance* E, *radiant energy* Q, or *radiant exposure* H (see Part I)). The respective SI units are given in previous documents of this series and in literature reference 2.

The input of a detector may consist of either monochromatic or polychromatic radiation. With monochromatic radiation the respective radiation quantity is contained in a narrow wavelength band $d\lambda$. Polychromatic radiation covers a certain wavelength range and has a characteristic distribution as a function of wavelength. The corresponding radiation quantities are defined as *spectral power* $\Phi_\lambda = d\Phi(\lambda)/d\lambda$ (unit: W nm^{-1}), *spectral irradiance* $E_\lambda = dE(\lambda)/d\lambda$ (unit: W m^{-2} nm^{-1}), *spectral radiant energy* $Q_\lambda = dQ(\lambda)/d\lambda$ (unit: J nm^{-1}), and *spectral radiant exposure* $H_\lambda = dH(\lambda)/d\lambda$ (unit: J m^{-2} nm^{-1}). In many cases it is appropriate to describe the radiant power by means of the number of *photons* or *quanta* arriving per unit time. (See table 4.1 in Part VI).

If the energy of one quantum is $J_q = h\nu = hc/\lambda$ (unit: J), where h is the Planck constant, ν the frequency, λ the wavelength and c the velocity of propagation of electromagnetic radiation in a vacuum, then the number N of quanta of a given radiant energy is $N = Q/J_q = Q/h\nu = Q\lambda/hc$. If Q has a spectral distribution characterized by the spectral radiant energy Q_λ, then the number of quanta for a given interval is $dN=(Q_\lambda \lambda/hc)d\lambda$ and the total number is

$$N = \left(1/_{hc}\right)\int Q_\lambda \, \lambda \, d\lambda$$

The *photon flux* is the number of photons per unit time, $\Phi_p = dN/dt$ (unit: s^{-1}). Similarly, the *photon irradiance* is defined as photon flux per unit area dA, $E_p = d\Phi_p/dA$ (unit: s^{-1} m^{-2}).

3 TYPES OF DETECTORS

A *radiation detector* is a device in which *incident radiation* produces a measurable effect. If this effect is a rise in temperature it is called a *thermal detector*. If it is a rise in pressure it is called a *photoacoustic detector*. In the case where an electrical signal is produced it is called a *photoelectric detector*. Photoelectric detectors can be classified as photo-emissive detectors and semiconductor detectors. Where the radiation produces a chemical reaction, it is termed a *photochemical detector*.

A detector yielding an *output signal* that is independent of the wavelength of the radiation over a specific region is called a *nonselective detector*. Where it is wavelength specific it is a *selective detector*. A detector having a *quantum efficiency* independent of the wavelength is a *nonselective quantum counter*. Different types of detectors may be used for *integrated* and *time-resolved measurements*. Other types of detectors are used for *spatially resolved measurements*.

Certain types of detectors are able to distinguish between different quantum energies. This property is described by the *energy resolution* ΔE and the *energy resolving power* $E/\Delta E$. These detectors are called *energy dispersive detectors*. In X-ray spectroscopy, the reciprocal $\Delta E/E$ is often used but this is discouraged.

4 DETECTOR PROPERTIES

Appropriate terms, symbols and units are listed in table XI.1.

Table XI.1. Terms, Symbols, and Units for measurable quantities for radiation detectors

Term	Symbol	Practical Unit	Notes
Responsivity	R	e.g. A W^{-1}	
Spectral Responsivity	$R(\lambda)$	e.g. A $W^{-1}nm^{-1}$	
Noise-equivalent-power	Φ_N	W	
Detectivity	D	W^{-1}	$D = 1/\Phi_N$

Term	Symbol	Practical Unit	Notes
Normalized detectivity	D^*	$W^{-1}mm\,Hz^{1/2}$	$D^* = D(A\Delta f)^{1/2}$
Detector sensitive area	A	mm^2	
Detector quantum efficiency at wavelength λ	$\eta(\lambda)$	1	
Detector sensitive volume	V	mm^3	
Frequency bandwidth	Δf	Hz	
Dark current	i_d	A	
Signal current	i_s	A	
Mean square noise current	$\sqrt{\overline{i_N}^2}$	A	
Load resistance	R_L	Ω	
Multiplier gain	G	1	
Signal-to-noise ratio	r_{SN}	1	$r_{SN} = i_s/\sqrt{\overline{i_N}^2}$
Dark resistance	R_d	Ω	
Time constant	τ_c	s	
Rise time	τ_r	s	
Fall time	τ_f	s	
Response time	τ_R	s	$\tau_R = \tau_r + \tau_f$

4.1 Responsivity

The *detector input* can be e.g. radiant power, irradiation, radiant energy. It produces the measurable *detector output* which may be e.g. an electrical charge, an electrical current or potential or a change in pressure. The ratio of the *detector output* and the *detector input* is defined as the *responsivity* R. It is given in e.g. ampere/watt, volt/watt. The responsivity is a special case of the general term *sensitivity*. *Dark current* is the term for the electrical output of a detector in the absence of input. This is a special case of the general term *dark output*. For photoconductive detectors the term *dark resistance* is used.

If the responsivity is normalized with regard to that obtained from a reference radiation the resulting ratio is called *relative responsivity*. For measurements with monochromatic radiation at a given wavelength λ the term *spectral responsivity* $R(\lambda)$ is used. In some cases the *relative spectral responsivity*, where the spectral responsivity is normalized with respect to the responsivity at some given wavelength, is used. The dependence of the spectral responsivity on the wavelength is described by the *spectral responsivity function*. The *useful spectral range* of the detector should be given as the wavelength range where the relative responsivity does not fall below a specified value.

4.2 Quantum efficiency

A figure of merit related to the responsivity is the *quantum efficiency* $\eta(\lambda)$. It describes the number of elementary events, e.g. electrons or pulses produced by one incident photon. In the case of photoelectric detectors where the output is a current the quantum efficiency is related to the spectral responsivity by means of $\eta(\lambda) = (s(\lambda)/\lambda)(hc/e)$ where e is the elementary charge.

The responsivity of a detector may depend on the degree of polarization of the incident radiation giving rise to a *polarization effect*.

4.3 Noise

All signals exhibit undesirable fluctuations that are called *noise*. The frequency distribution of noise is characterized by a *power spectrum*. Two different types of noise can be observed, *periodic* and *nonperiodic noise*. The periodic noise is usually observed as *high-frequency proportional noise*. The nonperiodic noise can be divided into noise observed only at low frequencies, the *excess low-frequency noise*, and noise independent of the frequency, the *white noise*. When the excess low-frequency noise is proportional to the reciprocal of the frequency, i.e. to $1/f^{\alpha}$ (with α close to 1), the noise is called *flicker noise*. *Drift* can be considered as noise with slow fluctuation. A noise is generally represented by a root mean square value (RMS) of the fluctuation, which is equivalent to a standard deviation provided a Gaussian distribution can be assumed.

Detector noise originates in the detector and can be classified as:

Thermal or *Johnson noise*[1] due to the thermal agitation of current carriers in a resistive element.

Temperature noise(mainly for semiconductor detectors) due to the statistical processes of heat exchange between the detector and its surroundings, which produces a fluctuation of the electric signal. It is especially important in the case of thermal detectors[2] (see section 5).

Generation-recombination noise due to the statistical nature of charge carrier generation and recombination processes.

Contact noise due to current fluctuations across electrical contacts.

Radiation noise due to statistical fluctuations in the "arrival" of the photons.

Dark current noise due to the sum of noise currents in the absence of a signal, including fluctuations of thermionic emission, of leakage current, of corona discharge charge carriers and other physical effects.

Shot noise is the sum of the radiation noise and the statistical component of the dark current noise.

4.4 Detectivity and related terms

The smallest signal that can be determined is limited by noise. The *noise equivalent power* Φ_N is the incident radiant power resulting in a signal/noise ratio of 1 within a bandwidth of 1 Hz and at a given wavelength. The reciprocal of the noise equivalent power is defined as *detectivity* D. It is useful to normalize the detectivity by referring it to the sensitive area A of the detector and the *frequency bandwidth* Δf of the measurement, resulting in the *normalized detectivity* D^*, which is defined by means of the following equation:

$$\begin{aligned} D^* &= D(A\,\Delta f)^{1/2} \\ &= (1/\Phi_N)(A\,\Delta f)^{1/2}\ [\mathrm{W^{-1}\ mm\ s^{-1/2}}]. \end{aligned}$$

It is recommended to report D^* in the form D^* (500 K, 900, 1) = ... or D^*_λ (5mm, 900, 1) = ... These refer respectively to the value of D^* for a 500 K black body, or a 5 mm narrow-band source as measured at a 900-Hz chopping frequency, and a 1-Hz noise bandwidth.

4.5 Linearity of responsivity

Linearity of responsivity describes the extent to which the output of the detector is directly proportional to the incident radiant power at a given wavelength and at constant irradiation geometry.

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[1]The term Nyquist noise is also sometimes used. The term Johnson noise is to be preferred.

[2]Consequently, the detectivity of thermal detectors increases on cooling, whereas the pyroelectric detector functions in a different way and its detectivity is not affected by temperature noise.

4.6 Temporal characteristics

Every detector has a time constant. If the output changes exponentially with time, the time required for it to change from its initial value by the fraction (1 - exp($-t/\tau_c$) (for $t = \tau_c$) of the final value, is called the *time constant* τ_c.

The *response time* τ_R is the time required for the detector output to go from the initial value to a percentage (e.g., 99%) of the final value. In the case of an exponential behaviour of the detector τ_R can be related to τ_c. The *rise time* τ_r is the time required for the detector output to vary between given percentages (e.g., from 10% to 90%) of the final value. Similarly, the *fall time* τ_f is the time required for the detector output to vary between given percentages (e.g., from 90% to 10%) of the initial value.

The *delay time* and the response time of the detector may be due to the *transit time* of *charge carriers* within the detector. The detector response to a hypothetical Dirac delta function input exhibits a final bandwidth, defined by the *spread time* τ_{sp}, which is due to τ_r and τ_f.

For constant input the output, and hence the responsivity, can change with time. If this change of responsivity with time is reversible it is called the *fatigue effect*. It may also be the cause of *hysteresis*. If, however, the change is irreversible, one speaks of *aging*. If an operating parameter e.g. the supply electric potential is changed, the responsivity may need time, i.e. the *settling time*, to reach the new final value.

The responsivity of the detector can be modulated on and off for time gating, for example to avoid detection of scattered excitation photons in a time-resolved fluorescence experiment.

4.7 Terms related to detector geometry

4.7.1 Detector sensitive area

The *sensitive area* is that area of the detector where an incident radiant power results in a measurable output.

4.7.2 Detector sensitive volume

The *sensitive volume* of the detector is that volume of the detector where an incident radiant power produces a measurable output.

4.7.3 Detector homogeneity

Detector homogeneity is specified by the *effective sensitive area* or the *effective sensitive volume* where the responsivity is homogeneous to within specified limits.

4.8 Temperature effects on responsivity

The dependence of a detector on temperature can be described by the *temperature coefficient of responsivity* and is expressed as percentage change in output per K. In the case of a nonlinear dependence the temperature and the temperature range should also be stated for which the stated temperature coefficient of responsivity is applicable.

5 THERMAL DETECTORS

Thermal detectors ideally exhibit a wide wavelength-independent response. Thermal detectors are amenable to absolute calibration. Thermal detectors so calibrated are called *absolute radiometers*.

5.1 Thermocouples

A *thermocouple* is based on the thermoelectric effect, by which two junctions between dissimilar conductors (metallic or heavily doped semiconductors) kept at different temperatures generate an electric potential. This potential depends on the amount of radiant energy absorbed by the *active junction*, while the *compensating junction* serves as a reference.

5.2 Thermopiles

A *thermopile* consists of several thermocouples connected in series to increase the magnitude of the electric potential.

5.3 Bolometers

A *bolometer* is a detector constructed from a material having a large *temperature coefficient of resistance*. Absorption of radiation gives rise to a change in resistance. A bolometer is named according to its active component, e.g. *thermistor bolometer, semiconductor bolometer, superconductor bolometer*.

5.4 Pyro-electric detectors

A *pyro-electric detector* is based on the temperature dependence of *pyro-electricity*. The material forms the dielectric in a small capacitor, and the change in surface potential is detected as the detector is intermittently irradiated.

5.5 Pressure-sensitive detectors

A pressure change as a result of the absorption of radiation is used for a *pressure-sensitive detector*.

5.5.1 Pneumatic detector

A *pneumatic detector* is based on the pressure increase of a gas. A special type is the *Golay cell* where the pressure change is detected by observing the deflection of one of the chamber walls.

5.5.2 Photo-acoustic detector

A *photo-acoustic detector* is used to detect intermittent radiation absorbed in a black body or in the sample concerned. The resulting rapid temperature change produces a *transient pressure oscillation* that is observed with the help of a *microphone*, or a *piezoelectric device*.

6 PHOTO-EMISSIVE DETECTORS

In a *photo-emissive detector*, a photon interacts with a solid surface, which is called the *photocathode*, or a gas, releasing a photoelectron. This process is called the *external photoelectric effect*. The photoelectrons are collected by an electrode at positive electric potential, i.e. the *anode*.

6.1 Vacuum phototubes (PT)[3]

The *vacuum phototube* is a photo-emissive detector inside an evacuated envelope with a transparent window, the photocathode, and the anode. The photocathode can be opaque or semitransparent.[4] The useful spectral range is determined by the spectral responsivity function or by the quantum efficiency function of the photocathode (often characterized by a so-called S-number) and the spectral transmittance of the window material. A special type, the *solar blind detector*, is insensitive to radiation of wavelengths longer than some specified wavelength (e.g. 320 nm) in the UV range.

Depending on the location of the *detector window* the PT is called a *end-on tube* or a *side-on tube*. For UV wavelengths and X-rays for which there is no transparent window material available the detector is operated without a window. Such a detector is called a *windowless detector*.

6.1.1 Low-potential vacuum phototubes

Low -potential vacuum phototubes are operated at electric supply potentials of 50 V to 250 V,. They can be well calibrated, and are used for absolute radiometric measurements.

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[3] The term vacuum photodiode is not recommended.
[4] The surface of the inner wall at the entrance can act directly as the photocathode.

6.1.2 Biplanar vacuum phototubes

Biplanar vacuum phototubes consist of a plane wire mesh anode and a plane opaque cathode separated by a few mm. Operated at electric supply potentials of up to 5 kV they have response times in the nanosecond range and are capable of delivering high pulse currents. They are used in pulsed laser applications.

6.2 Photomultiplier tubes (PMT)

A *photomultiplier tube* (PMT) is a vacuum phototube[5] with additional amplification by *electron multiplication*. It consists of a photocathode, a series of *dynodes*, called a *dynode chain* on which a secondary-electron multiplication process occurs, and an *anode*. According to the desired response time, transit time, *time spread*, gain, or low dark current, different types of dynode structures have been developed, e.g. *circular cage structure, linear focused structure, venetian blind structure, box and grid structure*. Some special dynode structures permit combination with additional electric or magnetic fields.

The *gain* of the photomultiplier is $G = k\sigma^n$, where k is the efficiency of collection of photoelectrons on the first dynode, σ is the secondary emission ratio, i.e. the number of secondary electrons emitted for each electron incident on the dynode, and n is the number of dynodes. The PMT is a high-impedance current generator.

6.2.1 Strip dynode photomultiplier tubes

The *strip dynode photomultiplier* tube consists of a photocathode followed by thin dynode material on an insulating substrate. In a *continuous-strip photomultiplier*, two strip dynodes are arranged in parallel. A potential applied to the ends of the two strips produces an electric field across the continuous strip dynodes, giving rise to *electron multiplication* along the dynodes. In a *resistance-strip magnetic photomultiplier*, a uniform magnetic field is applied to the planes of the strips, so that the electrons travel in the crossed electric and magnetic fields.

6.2.2 Channel photomultiplier tubes

A *channel photomultiplier tube*[6] consists of a photocathode, a *channel electron multiplier* (CEM) system for the photoelectrons, and an anode to collect the final electron current. The basic part of the CEM is a tube with a semiconducting inner surface. In general it is curved in order to inhibit the acceleration of positive ions towards the photocathode. A number of small channels called *microchannels* can be constructed in arrays for imaging applications (see 8.1.6).

6.2.3 Scintillation counters

The *scintillation counter* consists of a *scintillator* (see 9) coupled to a photomultiplier tube. Incident X-ray photons are converted in the scintillator into bursts of *visible light photons*, some of which fall on the photocathode and can be measured. For incident photons having energies higher than the absorption edge of the elements contained in the scintillator, an *escape peak* can be observed (see 6.4).

6.3 Gas-filled phototubes

A *gas-filled phototube* is similar in construction to a vacuum phototube except that it is filled with a noble gas (usually Ar) at a pressure of about 10 Pa. Photoelectrons accelerated by the anode electric potential ionize gas atoms. The additional electrons provide a substantial intrinsic gain.

6.4 Gas-filled X-ray detectors

Gas-filled X-ray detectors consist of a *cylindrical cathode* with a window, an *axial wire anode* and an ionizable gas. The gas may be continuously replenished giving a *flow-through detector* or the detector may be sealed. Following an original ionizing event, electron multiplication occurs through a process of *gas amplification* in the high electric field surrounding the anode wire. The *gain* of this process is defined as the number of electrons collected on the anode wire for each primary electron produced. For X-rays having

[5] All terms related to PT in 6.1 also refer to PMT, e.g. head-on PMT, solar-blind PMT.
[6] Use of the term channeltron is discouraged.

energies higher than the excitation potential of the *detector gas*, the spectral responsivity function has a second peak in addition to the main peak that is called the *escape peak.* The escape peak has a mean pulse height proportional to the difference between the photon energy of the incident X-rays and of the spectral characteristic line of the *detector gas.*

A *quenching gas*, a molecular gas, is added to the detector gas in order to neutralize the detector gas ions and to absorb secondary electrons as well as UV radiation resulting from neutralization of detector gas ions. According to the potential applied to the anode, the detector can work as an *ionization chamber, proportional counter*, or *Geiger counter*.

6.4.1 Ionization chambers

An *ionization chamber* is a gas-filled X-ray detector without any gas amplification.

6.4.2 Proportional counters

In *proportional counters* the electric potential is high enough for the gain to reach a value in the range from 10^2 to 10^5. Each electron produced by the initial photo-ionization causes one avalanche. Since the number of avalanche events is proportional to the energy of the incident photons, the charge collected by the anode is proportional to the X-ray photon energy.

6.4.3 Proportional gas-scintillation counters

The *proportional gas-scintillation counter* consists of a proportional counter coupled to an ultraviolet sensitive photomultiplier tube. Initial electrons produced by the interaction of the high-energy photon with the counter fill-gas are accelerated by a high electric field where they acquire sufficient energy to excite the noble gas atoms. The resulting UV radiation is observed by a photomultiplier tube.

6.4.4 Geiger counters

In *Geiger counters*, gas amplification reaches saturation and proportionality no longer exists. The output signal does not depend on the incident energy. The time taken for the counter to recover from the saturation is called *dead time*.

7 SEMICONDUCTOR DETECTORS

In a *semiconductor detector* photons are absorbed in the semiconductive material to produce electron-hole pairs. It employs the *internal photo-electric effect.* Electrons are raised from the valence band into the conduction band. Semiconductive materials can be either *intrinsic* or, if doped, *extrinsic*.

7.1 Photoconductive detectors[7]

In a *photoconductive detector* an electric potential is applied across the absorbing region and causes a current to flow in proportion to the irradiance if the photon energy exceeds the energy gap between the valence and the conduction band.[8]

Depending on their spectral responsivity function, photoconductive detectors are divided into photoconductive detectors for the visible wavelength range e.g. *cadmium sulfide* or CdS *photoconductive detectors*, photoconductive detectors for the near infrared wavelength range e.g. *lead sulfide* or PbS *photoconductive detectors*, photoconductive detectors for the infrared wavelength range e.g. *silicon doped with arsenide* or Si:As *photoconductive detectors*, and the *mercury-cadmium-telluride* or HgCdTe *photoconductive detector*.

7.2 Junction photodetectors, biased and unbiased photovoltaic detectors.

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[7] The alternative term "photoconductor" should not be used.
[8] Normally there are a number of conduction electrons available at room temperature, without any irradiation, giving rise to dark current.

7.2.1 Photodiodes

A *photodiode* is a two-electrode, radiation-sensitive junction formed in a semiconductive material. A *junction* is formed by two successive regions of a semiconductive material having, respectively, an excess of electrons (n-type) or holes (p-type). A bias potential applied to the detector creates a region at the interface that is depleted of majority carriers. Each incident photon produces electron-hole pairs in the depletion region resulting in a measurable signal current. The photodiode can be operated either with *zero bias* in the *photovoltaic mode* where the photodiode is actually generating the electric potential supplied to the load. In a biased mode, the *photoconductive mode*, the reverse current is proportional to the irradiation.

7.2.2. The Schottky-barrier photodiode

A *Schottky-barrier photodiode* is constructed by deposition of a metal film on a semiconductor surface in such a way that no interface layer is present. The barrier thickness depends on the impurity dopant concentration in the semiconductor layer. The incident radiation generates electon-hole pairs within the depletion region of the barrier where they are collected efficiently and rapidly by the built-in field.

7.2.3 PIN diodes (also for X-ray detection)

A *PIN (p-intrinsic-n) diode* is a *planar diffused diode* consisting of a single crystal having an *intrinsic* (undoped or *compensated*) *region* sandwiched between *p-* and *n-type regions*. A bias potential applied across the detector depletes the intrinsic region of charge carriers, constituting the radiation sensitive detector volume. The number of electron-hole pairs produced is dependent on the energy of the incident photons.

7.2.4 Avalanche photodiodes (APD)

An *avalanche photodiode* is a photodiode in which the photogenerated electron-hole pairs are accelerated by a bias potential near to *breakdown potential* so that further electron-hole pairs are formed leading to saturation of the photocurrent. This operational mode for photon counting is the so-called Geiger mode, similar to that of the gas filled Geiger counter. Avalanche photodiodes can also be operated in the proportional mode.

7.2.5 Phototransistors

A *phototransistor* is a *bipolar transistor* with its base-collector junction acting as a photodiode, which, if irradiated, controls the response of the device. Due to the inherent current *gain (of the transistor) the* responsivity of the phototransistor is greater than that of photodiodes.

7.2.6 Darlington phototransistors

A *Darlington phototransistor* consists of two separate transistors coupled in the high-impedance *Darlington configuration* with a phototransistor as the input transistor.

7.2.7 Field effect phototransistors (Photo-FET)

A *field effect phototransistor* or *photo*-FET is a *field effect transistor* (FET) that employs photogeneration of carriers in the channel region (the neutral region sandwiched between the insulator and the depletion region under the gate of the FET). It is characterised by high responsivity due to the high current gain of the FET.

8 SPATIALLY RESOLVING DETECTORS

Detectors for the measurement of the *spatial distribution* of the radiation, i.e. *spatially resolving detectors*, can be divided into two groups:

(i) the photosensitive area consists of a matrix of discrete photosensitive elements, the *pixels* (picture elements), forming an *array* with the facility to separately read out the information, simultaneously or sequentially.

(ii) the photosensitive area consists of a single photosensitive element that must be scanned (e.g., image dissection tube.)

A further distinction can be made between one and two-dimensional detectors that are *instantaneous* (nonstoring) or *time integrating* (storing). In addition, time integration can be intrinsic to the detector or can be performed by associated electronics. The *array geometry* is defined by the total photosensitive area of the detector, the dimensions of the pixels, and their *centre-to-centre spacing*, which mainly determines the *spatial resolution*. In the case of linear arrays its *geometry* is also determined by the height of the sensing area. *Dummy arrays*, as blanked-off portions of arrays, can be used to compensate for dark current. Readout from arrays can be either *sequential* or *random access* in multiplexed operation.

8.1 Instantaneous spatially resolving detectors

8.1.1 Photodiode arrays

An arrangement of a number of photodiodes on a single chip is a *photodiode array*. *Interchannel crosstalk* due to scattering of radiation or leakage of electric charges influences the detectivity of the respective element and the spatial resolution.

8.1.2 Pyroelectric photodetector arrays

A *pyroelectric photodetector array* consists of a monolithic array of pyroelectric detector elements arranged in one or two dimensions.

8.1.3 Image dissection tubes

An *image dissection tube* is a two-dimensional radiation detector in which the electron image produced by a photo-emitting surface, usually a photocathode, is focused in the plane of a *defining aperture*. Magnetic or electric fields scan this image across the defining aperture.[9]

8.1.4 Position-sensitive photomultiplier tubes

In *position-sensitive photomultiplier tubes* spatial resolution is obtained with the help of a partitioned photocathode.

8.1.5 Position-sensitive proportional counters

Position-sensitive proportional counters for spatially resolved detection of X-rays make use of both *single-wire* and *multi-wire* arrangements.

8.1.6 Microchannel plates (MCP)

A large group of microchannels (See 6.2.2) assembled in a block is called a *microchannel plate* (MCP). The MCP can be used as a position-sensitive detector with each channel acting as an independent electron multiplier. Gain limitations by ion-feedback can be overcome by juxtaposing two suitably cut and oriented MCPs to include a sharp bend at the junction (the *chevron orientation*) or by using curved channels. The electron cloud leaving the channels can either be directly detected or, indirectly by light conversion (see 9) using a fluorescent screen.

8.1.7 The Anger camera

X-ray imaging can be performed with an *Anger camera* in which a large diameter scintillator is coupled to an array of photomultiplier tubes by *fibre optics*. X-ray imaging may also be achieved in *multi-crystal cameras* where many small crystals individually scintillate.

8.2 Time-integrating spatially resolving detectors

8.2.1 Time-integrating photodiode arrays

Time-integrating photodiode arrays are photodiode arrays (see 8.1.1) with storage facilities by virtue of integrating capacitors in the associated electronics.

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[9] Normally, photoelectrons passing the defining aperture enter an electron multiplier chain for amplification and detection.

8.2.2 Vidicons

A *vidicon* is a vacuum tube containing a photosensitive area, or *target*, and an *electron gun* to read the signal from the target. The *silicon target* consists of a two-dimensional array of Si-photodiodes having a common cathode and isolated anodes. Irradiation of the target causes the production of electron-hole pairs which, by recombination, leads to a depletion of the surface charge. When the beam scans a depleted area, a *recharging current* flows. The time interval before the next measurement can be made, caused by the inability to completely recharge the depleted area by a single scan, is called the *lag*.

8.2.3 Silicon-intensified-target (SIT) vidicons

In a *silicon-intensified-target vidicon (*SIT *vidicon)* a curved photocathode is irradiated through a *fibre optic face plate*. The silicon target of a vidicon is then used to detect the accelerated and focused photoelectrons originating at the photocathode.

8.2.4 Charge transfer devices

A *charge-transfer device* has a *metal oxide semiconductor* (MOS) structure that is composed of many independent pixels where charge is stored in such a way that the *charge pattern* corresponds to the irradiation pattern. These devices can be linear or two-dimensional. According to the method used to detect the charge pattern, two types of charge-transfer devices can be distinguished: *charge-coupled devices* (CCDs) and *charge-injection devices* (CIDs).

8.2.4.1 Charge-coupled devices

In a *charge-coupled device* the signal charge is transferred to the edge of the array for readout. Alternatively, multiplexing can be used. The charge packets are transferred in discrete time increments by the controlled movement of *potential wells*. In a linear CCD the charge is moved in a stepwise fashion from element to element and is detected at the end of the line. A *two-dimensional array* CCD consists of a two-dimensional assembly of interconnected linear CCDs. Because the charge from wells located far from the output must undergo many hundreds of transfers, the *charge transfer efficiency*, or *CTE*, is of concern. The on chip summing of charges in adjacent pixels along rows or columns is called *binning*.

(i) The *full-frame array* has a single photosensitive array for photon collection, charge integration, and charge transport. It is read out a line at a time and incident radiation must be blocked during the readout process.

(ii) A *frame-transfer array* is composed of two arrays in series, the image and storage arrays. The storage array is covered with an opaque mask. After the image array is irradiated, the entire exposed electronic image is rapidly shifted to the storage array for readout. While the masked storage array is read out, the image array may acquire charge for the next image.

8.2.4.2 Thinned charge-coupled devices

Direct X-ray and broad wavelength-band imaging and detection can be performed by a *thinned CCD* irradiated from the side opposite the electrodes.

8.2.4.3 Charge injection devices (CID)

In a *charge-injection device* (CID) the accumulated charge is not transferred serially out of the array, but is shifted between two adjacent capacitors. In *nondestructive readout* the output is derived from the electric potentials on these two capacitors, which retain the information. Alternatively, the output can be derived from the stored charge after it has been injected into the substrate, thus destroying the original information.

8.3 Intensified arrays

An *intensified array* consists of an intensifier directly coupled to a diode or charge transfer array. The intensifier is composed of a semitransparent photocathode and a magnetically or electrostatically focused accelerating region. A *Digicon* is such a detector adapted to X-ray spectroscopy.

9 CONVERTERS

9.1 Wavelength converter

A *wavelength converter* converts radiation at one wavelength to radiation at another detectable wavelength or at a wavelength of improved responsivity of the detector. The classical wavelength converter consists of a screen of luminescent material that absorbs radiation and radiates at a longer wavelength. Such materials are often used to convert ultraviolet to visible radiation for detection by conventional phototubes. In X-ray spectroscopy a converter that emits optical radiation is called a *scintillator*. In most cases wavelength conversion is from short to long wavelength, but in the case of conversion of long to short wavelength the process is sometimes called *upconversion*. Wavelengths of coherent sources can be converted using *nonlinear optical techniques*. A typical example is *frequency doubling*.

9.2 Image converter tube

An *image converter tube* is an electron tube that produces on its fluorescent screen an image of the irradiation pattern of its photosensitive input surface. An image converter which produces an image with enhanced radiance is sometimes called an *image intensifier*.

9.3 Streak tube

An image converter adapted to provide scanning or time-resolved images is called a *streak tube*. If the image is recorded the whole device is an example of a *streak camera*.

10 LITERATURE

The following IUPAC publications deal with aspects covered in this document:

1. IUPAC Manual of Symbols and Terminology for Physicochemical Quantities and Units, 2nd revision (Pure Appl. Chem., 51, 1-41 (1979).

2. IUPAC Quantities, Units, and Symbols in Physical Chemistry, 2nd Edition (Blackwell Scientific Publications, Oxford, 1993).

3. IUPAC Compendium of Analytical Nomenclature, Definitions, and Rules, 2nd Edition (Blackwell Scientific Publications, Oxford, 1987).

The definitions of the Commission Internationale de l'Eclairage (CIE) ("International Lighting Vocabulary", Publ. No. 17, CIE, Paris) have been used wherever feasible.

In addition, the books Physical Detectors of Radiation by W. Budde, (Academic Press, New York, 1983), Optical Radiation Detectors by Eustace L. Dereniak and Devon G. Crowe, (John Wiley & Sons, New York, 1984), and Optical and Infrared Detectors, Edited by R. J. Keyes, Topics in Applied Physics Vol. 19 (Springer-Verlag, Berlin, 1977) have been extensively consulted.

11 ALPHABETICAL INDEX OF TERMS