
Ionizing Radiation Detectors

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<http://dx.doi.org/10.5772/60914>

Abstract

Ionizing radiation has always been present in the natural environment. However, this radiation is not easily detected and since it also possesses high ionizing power and penetration strength, it constitutes a risk to human health when it is found outside of its acceptable limits. The adverse effects of ionizing radiation on human health need to be systematically monitored in order to prevent damage, overexposure, or even death. The detection of the radiation depends on its particular interaction with a sensitive material, and different types of detectors, in different physical states (solid, liquid or gas), are used to measure selective types of ionizing radiation. New materials such as organic semiconductors, for instance, are being targeted for research and as potential candidates for new perspectives on ionizing radiation sensing.

Keywords: Radiation, high energy, detector

1. Introduction

Ionizing radiation has always been present in the natural environment. Sources of ionizing radiation are commonly found in water, air, soil, or manmade devices. However, ionizing radiation is situated in the electromagnetic spectrum outside the region of perception of the human eye - visible region - and it has no smell. Thus, it cannot be detected by the human senses. Since the ionizing radiation is not easily detected and it also possesses high ionizing power and penetration strength, it constitutes a risk to human health when it is found outside of its acceptable limits. The adverse effects of ionizing radiation on human health need to be systematically monitored in order to prevent damage, overexposure, or even death. The ability to identify sources of radiation, specific radioisotopes, and measure quantities of radiation is

crucial to environmental monitoring, radiation protection, and development of security programs.

Ionizing radiation cannot be directly measured. The detection is done indirectly using an ionizing radiation sensitive material, which constitutes the basis when developing sensors or detectors of radiation. However, there is not a radiation detector that can measure all types of radiation efficiently. The interaction of radiation with matter depends on the nature of the radiation: the electromagnetic radiation, light charged particles, neutrons, or heavy charged particles. Therefore, a detector which efficiently measures a particular kind of radiation could be completely inappropriate for others. The nature of the sensitive material's response to the ionizing radiation and its energy range to be measured will determine the type of detector.

When the ionizing radiation interacts with a sensitive material constituting the detector device, it generates a signal, which can be a pulse, hole, light signal, and many others [1]. The detection of the radiation depends on the particular interactions with the sensitive material, and there are three main and well-established possibilities to relate and categorize the induced radiation with the generated signal in the detector, as shown below:

- i. The generated signal from the incident radiation is created by the counting of the number of interactions occurring at the sensitive volume of the detector. In this case, the detector is called *counter*.
- ii. The incident radiation generates a signal that measures the energy that has reached the detector. The detector is named *spectrometer*.
- iii. The detector measures the average energy incident on a specific point of the sensitive volume, that is, the absorbed radiation dose. Such detectors are known as *dosimeters*.

A priori or *a posteriori* application of ionizing radiation detector will indicate which type is more suitable to use for a specific measurement. To measure the radiation in real time, as in the case of evaluating the average radiation of a given location, direct-read instruments such as gas detectors, scintillation detectors, or semiconductor detectors are used. In order to measure the radiation to which a person is exposed, detectors that can be further processed such as photographic emulsions and thermoluminescent dosimeters are used.

Radiation detectors have to two key principles: (i) ionization and (ii) excitation. In ionization-based detectors, electron-ion pairs are generated by enough energy when ionizing radiation reaches atoms of a sensitive material and removes orbital electrons (Figure 1).

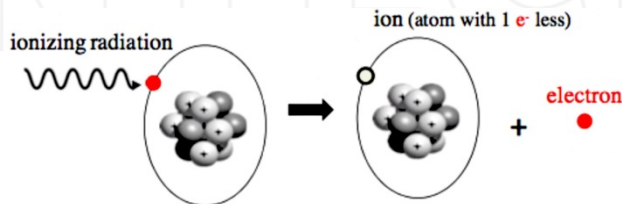


Figure 1. Ionization Process.

In excitation-based detectors, bounded electrons are raised to an excited state in the atom or molecule when part of the radiation energy is transferred to them (Figure 2). The electron excited to these states returns to its ground state emitting light in the UV-Visible region.

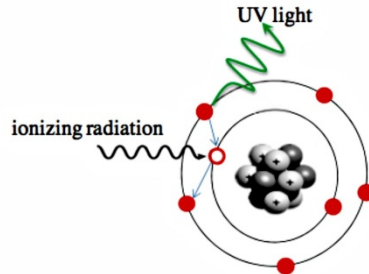


Figure 2. Excitation process.

2. Detectors

2.1. Gas-filled detectors

When a high-energy radiation passes through a medium, it undergoes ionization and releases charges that depend on the excitation radiation energy. In gas detectors, the ionization appears as electron-ion pairs and these charge carriers can be attracted and collected by electrodes [2-4].

In gases, ionized particles can travel more freely than in a liquid or a solid. Therefore, in gas counters the space between the electrodes is filled with a gas and when a voltage is applied an electric field is created by the potential difference between the electrodes. Electrons and positively charged gas atom of each ion pair accelerate to anode and cathode, respectively, resulting in an electric signal (current) in the circuit that can be correlated to radiation exposure and displayed as a value (Figure 3).

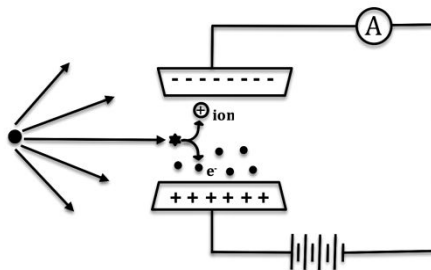


Figure 3. Current mode.

Another detection possibility is to acquire the incident radiation signal through pulses (pulse counting mode). In this case, the number of ion-electron pairs generated corresponds to the intensity of the detected pulse (Figure 4). The ionization chamber, proportional counters, and Geiger-Muller counters are examples of gas detectors. Typically, ionization chambers are used in the current mode while proportional counters and Geiger-Muller use the pulse mode to measure the radiation.

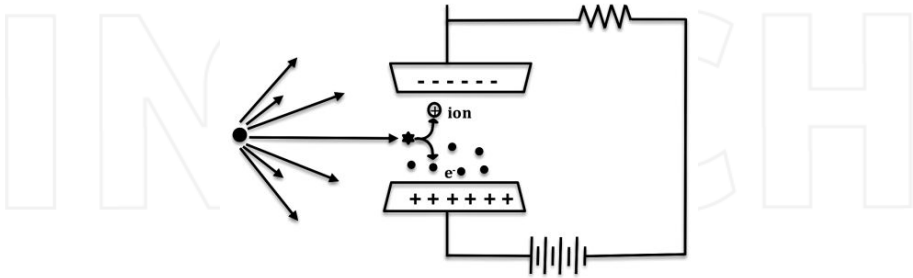


Figure 4. Pulse mode counting.

The average energy W required to produce an electron-ion pair varies (20-45eV) depending on the gas used. The average energy W can be expressed as [5]:

$$W = \frac{E_i}{\langle N \rangle} \quad (1)$$

where E_i is the energy deposited by the incident radiation and N the average number of electron-ion pairs formed.

The number of ion pairs generated varies according to the applied voltage for constant incident radiation. The voltages can vary widely depending upon the detector geometry and the gas type and pressure. The different voltage regions are indicated schematically in Figure 5. There are six main practical operating regions, where three are useful to detect ionizing radiation.

Region (1): At low voltage, the electric field is not large enough to accelerate electrons and ions. Then, many electrons and ions produced in gas recombine before they reach the electrodes and they are not collected. In this area, the size pulse increases as applied voltage increases, and the recombination rate decreases to the point where it becomes zero. This first region is called recombination and is not useful for counting radiation.

Region (2): In the ionization region, the voltage is high enough and each ion pair generated reaches the electrodes. However, the number of the ion pairs does not change when voltage is increased and the curve is flat. Then, the number of ion pairs produced by the radiation is nearly equal to the number of ion pairs collected by the electrodes because there is no recom-

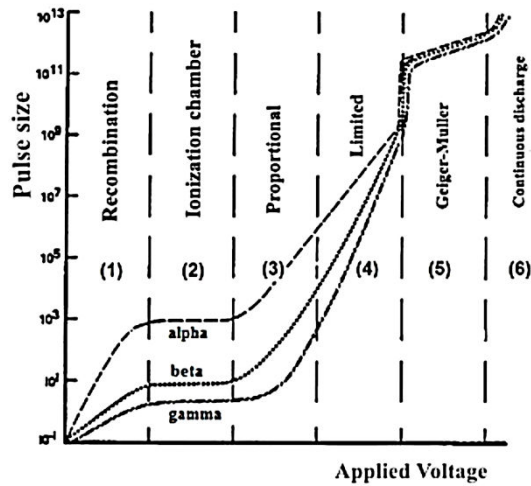
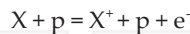


Figure 5. Six-region curve for gas-filled detectors.

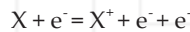
Recombination and the voltage is not high enough to produce gas amplification. The ionization chambers work in this region.

Region (3): In the proportional region, there is a gas amplification that causes more ion pairs to reach the electrodes than ion pairs are initially produced by radiation. The electrons from the primary ionization acquire enough energy between collisions to produce additional ionizations due to strong electric field. These secondary ions formed are also accelerated causing an effect known as Townsend avalanches, which creates a single large electrical pulse.

Primary ionization



Secondary ionization



where X is the gas atom, p is the charge particle traversing the gas, and e is the electron.

The number of ion pairs collected divided by the number of ion pairs produced by the primary ionization provides the gas amplification factor. For example, if 50,000 ion pairs are collected and 10,000 ion pairs were initially produced, the gas amplification factor is 5. The gas amplification factor varies according to the applied voltage across the electrodes and it also varies with the geometry of the detector. However, it is constant at a specific voltage and for

any kind of radiation or energy of radiation. Then, if a voltage increases the gas amplification factor increases proportionally, but if a voltage remains constant the gas amplification factor also does not change. Because of this amplification process, proportional counters are extremely sensitive ($<10\text{KeV}$) while ionization chambers are limited by discriminate particles of $>10\text{ keV}$ energy.

The pulse height depends on the detected particle energy. Therefore, different energies of radiation can be distinguished by analyzing the pulse height. For instance, the size pulse from an alpha particle, for a fixed applied voltage, will be larger than the signal from a beta particle. Thus, particle identification and energy measurement are possible by using proportional counters.

Region (4): In the limited proportional region, the gas amplification factor is not constant for a given voltage setting and there is no proportionality of the output signal to the deposited energy at a given applied voltage. Additional avalanches occur, leading to additional ionizations and nonlinear effects take place. The nonlinearities observed are due to the high positive ion concentration, which leads to distortion in the electric field. Free electrons due to their high mobility are quickly collected by the electrodes while positive ions are slowly moving. Then, clouds of positive ions are created near the electrode, leading to distortions in gas multiplication. This region is usually avoided as a detection region.

Region (5): At high voltages, the electric field is so strong that avalanches of electron-ion pairs are produced and reach the electrodes. A strong signal is produced by these avalanches with shape and height independently of the primary ionization and the energy of the detected photon. This region is called the Geiger-Muller region, and the large output pulse is the same for all photons. Therefore, the energy or even incident radiation particle cannot not be distinguished by GM detectors.

Region (6): At still higher voltages (above GM region), the electric field strength is so intense that it itself produces ionization in the gas and completes avalanching. Continuous electric discharges occur between the electrodes and the detectors that operate in this region can be damaged. Therefore, no practical detection of radiation is possible.

2.2. Scintillation detectors

Scintillators are materials that exhibit luminescence when excited with ionizing radiation. The scintillation mechanism can be explained by means of the energy-band theory. In this model, a band gap separates the valence band (filled band) of conduction band (usually empty). Thus, via the ionization process, an electron can be excited from the valence band to the conduction band or to the energy states located close to the mid-gap (impurities). An exciton is formed when the electron removed remains electrostatically bonded with the hole left in the valence band. The electron excited to these states decays to the ground state emitting light in the visible range of the electromagnetic spectrum [6]. This visible light interacts with the photocathode and electrons are emitted by photoelectric effect and/or Compton scattering, producing a current in the circuit. However, scintillation detectors produce currents of low intensity and only after the advent of photomultiplier tubes has its use become feasible. In this way, the

electrons emitted by photocathode are multiplied by the dynodes in the photomultiplier tube and collected in the anode. As a result, a measurable electrical current is acquired. The output pulse of electrons of a scintillation detector is proportional to the energy of the original radiation.

A good scintillator material is highly efficient in converting incident radiation energy into light. The scintillator must also be transparent to its own light emissions and it must have a short decay time because the transparency is important to a good light transmission to reach the electrode, and the short decay time allows fast response.

Decay time is the time required for scintillation emission to decrease to e^{-1} of its maximum and it can be described as the sum of two exponential components [7, 8]:

$$i(t) = \frac{\omega}{\tau_0} e^{-t/\tau_0} + \frac{1-\omega}{\tau_1} e^{-t/\tau_1} \quad (2)$$

where τ_0 and τ_1 are the decay time constants of the fast and slow components of a scintillator, respectively, and ω is the weight of the fast component.

The fast component is related to the fluorescence and the slow component is related to phosphorescence or afterglow. These two types of radiative processes (photon emission processes) are well-established in the literature and they are illustrated by the Perrin-Jablonski diagram in Figure 6. The fluorescence occurs in the de-excitation process between singlet electronic states (same spin multiplicity), and it is responsible for the majority of emitting radiative processes due to short decay time (10^{-9} s). The phosphorescence occurs in de-excitation process between different multiplicity states (triplet-singlet), in times the order of 10^{-3} s. The singlet states are represented by S_n and triplet states by T_n , where $n = 0, 1, 2, 3, \dots$, and $n = 0$ corresponds to the ground state [8, 9]. Other type of delayed emission is the delayed fluorescence (DF), which is a reverse intersystem crossing $T1 \rightarrow S1$, it is induced thermally or by collisions. Afterglow competes with the scintillation process leading to a decrease of total efficiency of conversion of ionizing radiation into light, and it should be avoided in scintillation detectors [10].

Scintillation detectors are composed of two basic types of detector materials: organic and inorganic. Inorganic scintillators have scintillation properties due to their crystalline structure or due to activators (impurities), which enable scintillation process. Organic scintillators do not need crystal structure or activators because each molecule can act as a scintillation center. The difference in their behavior comes to the different ranges of energy levels excited by the incident radiation. Inorganic scintillators usually respond more slowly than organic scintillators, but they are more efficient than organic materials for detecting ionizing radiation because of their greater density and higher average atomic number. However, organic materials are more flexible and cheaper than inorganic material, leading to numerous scientific efforts to increase their performance in recent decades.

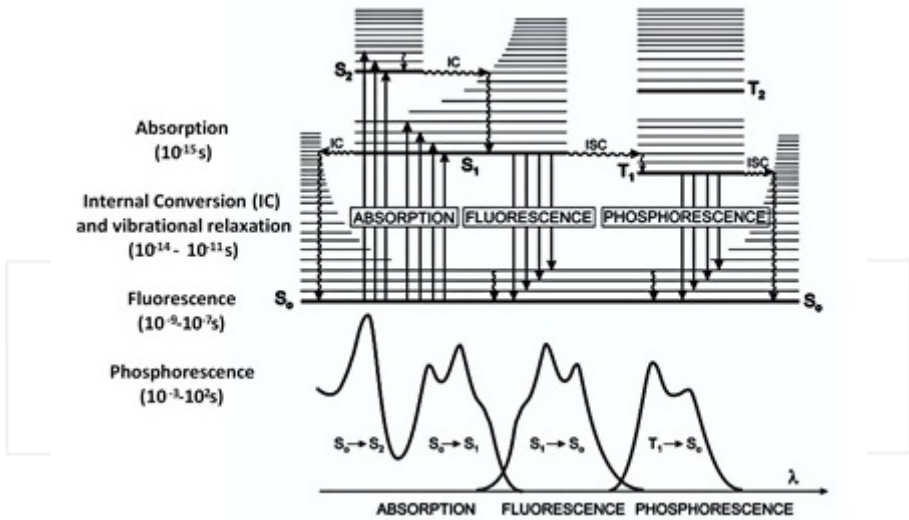


Figure 6. Perrin-Jablonski diagram.

Currently, the scintillation detectors have excellent sensitivity to excitation energy and fast response time. Different types of scintillators, in different physical states (solid, liquid, or gas), are used to measure selective types of ionizing radiation. They are widely used in medical applications for image generation (X-rays and tomography), as well as high-energy physics experiments, plant laboratories, airports security (X-rays machines), and radiation sensing for nuclear installations.

2.3. Semiconductor detectors

Semiconductors are materials, inorganic or organic, which have the ability to control their electronic conduction depending on chemical structure, temperature, illumination, and presence of dopants. The name semiconductor comes from the fact that these materials usually present an intermediate conductivity between conductors and insulators. Consequently, they have an energy gap less than 4eV [11]. In solid-state physics, energy gap or band gap is an energy range between valence band and conduction band where electron states are forbidden. The valence band is the region where electrons are connected to the lattice atoms. The conduction band is the region that contains the energy levels where free electrons can move through the crystal structure [12, 13]. The width of the forbidden energy band is what categorizes the material as conductor, semiconductor, or insulator (Figure 7).

There are many semiconductors in nature and others synthesized in laboratories; however, the best known are silicon (Si) and germanium (Ge). Silicon has been considered precursor to the revolution that has occurred in recent decades in the electronic area. However, germanium is more used than silicon for radiation detection because the average energy necessary to create

an electron-hole pair is 3, 6eV for silicon and 2, 6eV for germanium, which provides the latter a better resolution in energy. In addition, in gamma spectroscopy, germanium is preferred due to its atomic number being much higher than silicon and which increases the probability of γ -ray interaction.

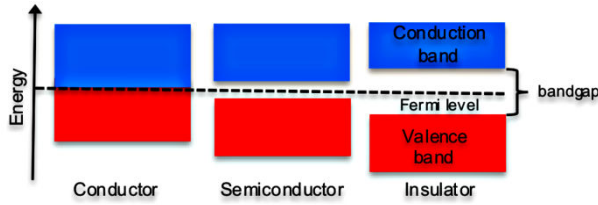


Figure 7. Band structure for electron energies in solids.

In semiconductor detectors, also called solid-state detectors, charge carriers are produced and collected by electrodes as in ionization chambers. However, the charge carriers are electrons and holes and not electrons and ions as in ionization chambers. When semiconductor detectors are subjected to high-energy radiation, electron-hole pairs are produced and converted into electric current.

The electron mobility in a gas counter is thousands of times greater than that of the ions. In fact, the electron mobility in semiconductors is roughly equal that of the holes and both types of carriers contribute to conductivity.

Conductivity is the inverse of resistivity and it is defined by

$$J = \sigma E \quad (3)$$

where J is the current density (A/m²), σ is the conductivity [A/(V.m)], and E is the electric field (V/m).

Another expression for the current density is:

$$J = eNv \quad (4)$$

where N is the number of charge carriers, e is the elementary charge, and v is the speed of carriers.

The following equation is obtained by using Equations 3 and 4:

$$\sigma = eN \frac{v}{E} \quad (5)$$

The ratio v/E is called carrier mobility μ :

$$\mu = \frac{v}{E} \quad (6)$$

The expression for the conductivity becomes:

$$\sigma = e(N_e \mu_e + N_h \mu_h) \quad (7)$$

where N_e and N_h are carrier concentrations and μ_e and μ_h are the mobilities of electrons and holes, respectively, and according to this equation, the conductivity changes if the mobility of charge carriers and/or their concentrations change. Thus, both terms in the right-hand side of Equation 7 contribute to the conduction in semiconductor detectors.

A small energy is required to create an electron-hole pair in semiconductor materials (~3 eV for germanium) compared to the energy needed to create an electron-ion pair in gases (~30 eV for typical gas detectors) or to create an electron-hole pair in scintillators (~100eV) [14]. As a consequence, a great number of electron-hole pairs are produced and reach the electrodes, increasing the number of pairs per pulse and, then, decreasing both statistical fluctuation and signal/noise in the preamplifier. This generates a big advantage over other detectors and the output pulse provides much better energy resolution. Moreover, the small sensitive area used to detect radiation (few millimeters) and the high speed of charge carriers provide an excellent charge collection time ($\sim 10^{-7}$ s).

The energy resolution, R , determines the ability of the system to distinguish two energies that are very close to each other, and that constitute an important parameter in the spectral detection of ionizing radiation (Figure 8). It is commonly defined as:

$$R = \frac{FWHM}{H_0} \quad (8)$$

where FWHM is the full-width-at-half-maximum and H_0 is the peak centroid.

In order for a semiconductor to act as a radiation detector, the active area to radiation must be free of excess electrical charges (depleted). The depletion region can be formed through the use of very high purity materials like High Purity germanium (HPGe) or PN junctions. PN junctions are obtained when an n-type semiconductor (excess of electrons) is placed in contact with a p-type semiconductor (excess of holes). Then, electrons and holes diffuse from n-region to p-region and from p-region to n-region, respectively, and they recombine around the interface. The ions, which are left behind by electrons and holes that were recombined, create an electric field that will attract more electrons and holes until there is no more charge carriers to recombine (Figure 9).

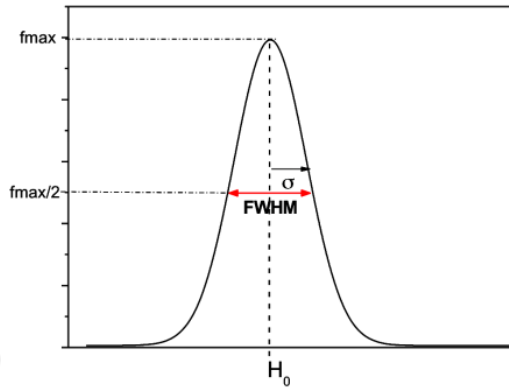


Figure 8. FWHM for a Gaussian distribution. In this case, the FWHM results related to the σ as $\text{FWHM} = 2.35 \sigma$.

At this moment, if the ionizing radiation interacts with the semiconductor in this depleted region, electrons are raised to the conduction band leaving behind holes in the valence band and producing a large number of electron-hole pairs. If a voltage is applied across the semiconductor, these carriers are readily attracted to the electrodes and current flows into circuit resulting in a pulse. The size of the pulse is directly proportional to the number of carriers collected, which is proportional to the energy deposited in the material by the incident radiation.

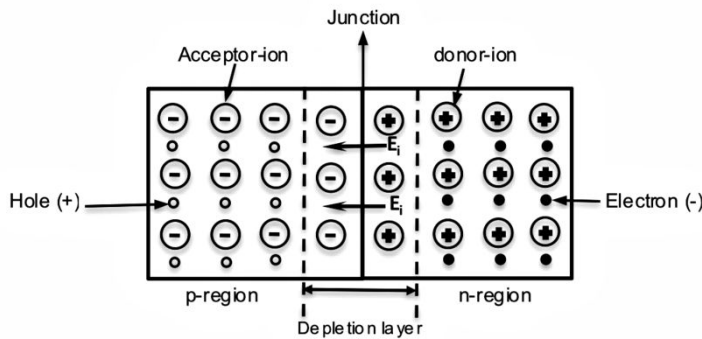


Figure 9. PN junction.

In semiconductors, if the temperature increases, electrons can be thermally excited from the valence band to the conduction band. Consequently, some semiconductor detectors must be cooled so as to reduce the number of electron-hole pairs in the crystal in the absence of radiation. Although solid-state detectors can be manufactured much smaller size than those of equivalent gas-filled detectors and they have short response time, seconds compared to the

hours of TLD detectors, they are still expensive because they need to be cooled. Thus, they are used when higher resolution is required; if higher efficiency is necessary, scintillation detectors are used.

Different semiconductor materials and device arrangements are used, depending on the type of radiation to be measured and the aim of application. The types of radiation that can be measured with semiconductor detectors comprise a large range of the electromagnetic spectrum: <1 eV to ~10 MeV for photons and energies above keV for charged particles. Commonly, semiconductor detectors are employed for beta particles or gamma radiation because the heavy charged particles cause more radiation damage. They are widely used in nuclear power station electronic dosimeters and portable survey instruments in gamma spectroscopy systems.

2.4. Thermoluminescent dosimeters

The amount of radiation absorbed by the human body can be determined through radiation dosimetry. A dosimeter has to correlate the absorbed radiation with biological effects induced in humans. The physical quantity that quantifies this relationship is called *absorbed dose*. The absorbed dose, D , of any ionizing radiation can be considered as the amount of energy given to the medium by ionizing particles or photons per unit of mass dm [2, 14, 15]:

$$D = \frac{d\bar{\epsilon}}{dm} \quad (9)$$

where $d\bar{\epsilon}$ is the average energy deposited by the radiation on a point P .

The SI unit of absorbed dose is the Gray (Gy), defined as: 1Gy = 1 J/kg. The obsolete units for dose are the rad (radiation absorbed dose) and the centigray (cGy): 1rad = 10^{-2} J/kg = 1cGy.

Thermoluminescent dosimeters (TLDs) are the foremost used devices for personal dosimetry. They are composed of crystal devices that emit light when are heated. The TLD reading device is able to calculate the amount of light released during heating, which can then be correlated with the absorbed dose received and stored by the TLD dosimeter.

A useful model of the thermoluminescence mechanism is provided in terms of the band model for solids. Thus, when a thermoluminescent crystal is exposed to ionizing radiation, electrons are quickly promoted to their conduction band through direct excitation process. However, some electrons are trapped by metastable states and when the material is subjected to thermal stimulation, they have enough energy to leave the trap states and recombine with holes that were left in the valence band. The excess of energy in this process is conserved by radiative deactivations emitting light, which is proportional to the absorbed ionized dose [16].

Figure 10 shows a model of energy bands with electronic transitions in thermoluminescence process.

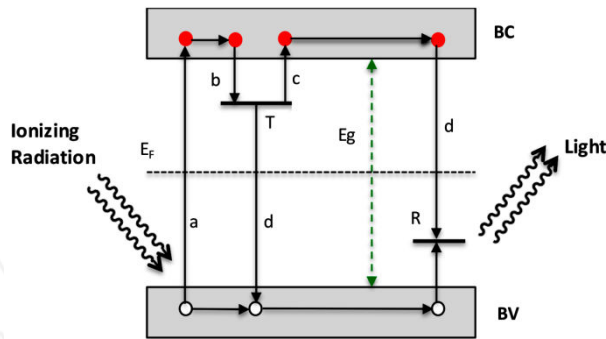


Figure 10. Model of energy bands in thermoluminescence process. (a) excitation and generation of electron-hole pair, (b) trapping, (c) de-trapping by thermal stimulation, (d) recombination. T is the center of the trap, R is the recombination center, E_F is the Fermi level, and E_g is the bandgap.

The heating of the TLD dosimeter to assess the accumulated radiation dose is done in temperature ramps and each temperature value is associated with a value of the light intensity (Figure 11). Thus, through thermoluminescence photons emission it is feasible to establish a curve of thermoluminescence intensity versus temperature that is called TL glow curve. The area under the TL glow curve is directly proportional to the number of emitted photons and, thereby, proportional to radiation dose received.

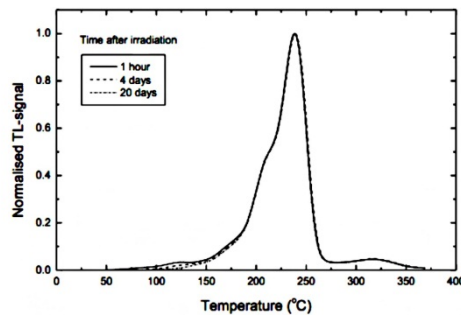


Figure 11. TL glow curve of LiF:Mg, Ti measured with a TLD reader at a low heating rate.

Thermoluminescent crystals possess good levels of deeper traps that require greater thermal energy to release the carrier, thus they can accumulate energy for a longer period of time. Many materials are purposely doped to create impurity levels; others such as LiF (lithium fluoride) already have natural impurities and intrinsic defects. Other substances are used as materials for thermoluminescent dosimetry, for example, CaSO₄:Dy (calcium sulfate doped with dysprosium); the CaSO₄:Mn (calcium sulfate doped with manganese); and CaF₂ (fluorite).

A thermoluminescent crystal can be used as dosimeter only if it presents high emission efficiency, good stability on temperature ranges of work, high resistance to environmental variations and linear radiation dose-response.

The principal advantages of TLD dosimeters are:

- High sensitivity over a wide dosage range.
- Small and varied forms.
- Can be used several times.
- They are equivalent to human tissues.
- They have high degree of accuracy and precision in the measurements.

Among the disadvantages are:

- Infeasibility of rereading.
- The necessary instrumentation for the measurement has high cost.
- Sensitivity varies with the time after irradiation.
- Readings and the results are not immediate.
- They present fading for sensitivity to light and moisture.

2.5. Chemical detectors

In chemical dosimetry, the ionizing radiation produces chemical changes in the medium that can be measured by using a suitable measuring system. Oxidation, reduction, and chemical dissociation are the principal mechanisms of chemical detectors.

The intensity of these changes is characterized by radiation chemical yield (G), which is defined as a number of molecules, ions, atoms, or free radicals of product or dissolved reaction components for 100 eV of absorbed energy, or even defined as the mean number of moles produced/destroyed by mean energy transmitted to the matter [2]:

$$G = \frac{\bar{n}}{\bar{E}} \quad (10)$$

where \bar{n} is the mean moles number and \bar{E} is the mean transmitted energy. G SI unit is mol.J^{-1} .

The most widely used chemical dosimetry standard is the Fricke dosimeter. The Fricke dosimetry system provides a reliable means for measurement of absorbed dose to water by ferrous ions oxidation. The dosimeter consists of a solution with 1 mmol/l ferrous sulfate (or ferrous ammonium sulfate), 1 mol/l NaCl, and 0.4 mol/l sulfuric acid. When the Frick solution is irradiated, the ferrous ions, Fe^{2+} , are oxidized by radiation to ferric ions, Fe^{3+} [17]. The ferric ion concentration is determined by spectrophotometry, which measures absorption peaks at

wavelengths of 224 nm and 304 nm. In this case, G-value is defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution. The usual range of the Fricke dosimeter is from 30Gy to 400 Gy.

2.6. Calorimetric detectors

Calorimetric methods measure the dose of radiation by measuring the temperature increase in a medium. Although the basic principles of calorimeters are very simple, they have technical problems to ionizing radiation sensing and they have been viewed as complex to make and operate [18]. Small temperature response to low dose of radiation and necessity of extremely thermic isolation are some problems of this type of detector. Therefore, few laboratories use these detectors; however, efforts have been made in order to increase their performance.

2.7. New materials to ionizing radiation sensing

Despite the well-established known techniques and detectors for ionizing radiation, the field still has a lack of new materials and sensor devices. The use of ionizing radiation in industrial processes, in clinics, hospitals, universities, and research centers has increased considerably and consistently in the past few years. In addition, the inspection and monitoring of aircrews is a current concern and should be mandatory to all flights in the near future. Thus, the development of new materials sensitive to ionizing radiation and robust devices, faster and more accurate, is of crucial importance to this research field and its direct applications.

In the last two decades, there was an effort to combine the energy sensitivity found in semiconductor devices with the low cost and flexibility of organic semiconductor-based conjugated polymers. In this fashion, oligomers and polymers such as PPV (poly p-phenylene vinylene) [19], MEHPPV (poly (2-methoxy, 5- (2 -ethyl-hexoxy) -p-phenylene vinylene) [20, 21], P3HT (poly 3-hexylthiophene) [22, 23], and pentacene [24] have become the target of research and are potential candidates for new perspectives to ionizing radiation sensing. Use of these materials, which have known properties and have been studied, have played an important role in the study of ionizing radiation effects on polymers (Figure 12).

In the interaction of high-energy radiation with semiconductors, primarily there occur excitations and ionizations that generate ions and electrons. The electrons generated (primary electrons) will interact again with the environment and generate secondary excitations that will produce electron-hole pairs. Therefore, the efficiency of the material with the highly energetic radiation will depend on its stopping power or absorption efficiency, the limited capacity of producing electron traps and its ability to grow large areas. Semiconductor polymers generally have high efficiency luminescence and absorption in the UV-Vis region; they can also form films producing large areas, and, hence, they constitute a new alternative in the area of radiation detectors.

In the field of electromagnetic radiation, there are several possible interactions of the most energetic radiation with matter: mainly, the photoelectric effect, Rayleigh scattering, Compton effect, and production of electron-positron pairs. Eventually, these interactions can lead to temporary or permanent modifications. These changes are called effects of degradation. They

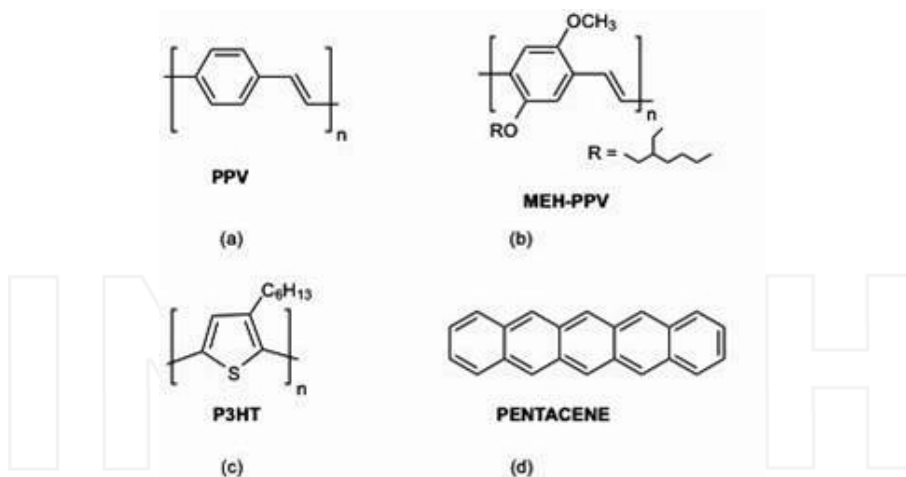


Figure 12. Chemical structure of polymers: (a) PPV (b) MEHPPV (c) P3HT and (d) pentacene.

may be superficial when there is change only in the physical appearance (color, transparency, etc.) or they may be structural.

Polymer degradation effects have been reported such as scission [25], cross-linking [26, 27], and photobleaching [28]. In scission, there occurs break of the main chain into smaller molecules, reducing its molecular weight. In cross-linking, due to link between two polymer chains or between two big radicals, there is a formation of an insoluble portion with increasing molecular weight. Decrease in viscosity and increase of ductility are effects of scission. Increase of hardness, viscosity, and brittleness are some of the macroscopic effects of cross-linking. Photobleaching occurs when the fluorescent signal of a fluorophore disappears permanently due to photon-induced chemical damage and covalent modification.

Degradation effects are often considered problems such as the oxidation effects of medical implants based on polyethylene after irradiation sterilization, for example [29]. However, the ionizing radiation degradation effects are not sometimes bad results. Many times they are desirable, as in the creation of integrated circuits, decreasing the molecular weight to make a material compatible with the other, in polysaccharides, for use in health care products, cosmetics, textile and food industry, or even to increase viscosity or resistance materials, for instance [30-32].

Polymer interaction with gamma radiation has been studied since the 1970s and different effects have been observed depending on the chemical structure of the polymer and the energy range used for irradiation process. The mechanisms involved in the interaction of gamma radiation with polymers have not been fully elucidated, but changes in conductivity and optical properties have been reported mainly in polyaniline [33] and on PPV and its derivatives. The results indicate the feasibility of using semiconductor polymers as gamma radiation detectors.

The interest in the use of conductive polymers in this area is due to the adjustability of its luminescence properties and conductivity, and they also have a lower cost than inorganic semiconductors. However, the use of polymers as radiation sensors is recent and few studies are reported in the literature. Among them, the highlighting results are P3HT as the active layer of OLEDs and OFETs for sensing radiation [20], and the MEH-PPV in halogenated solutions for detection of low doses of gamma radiation.

Studies using MEH-PPV have demonstrated that the use of solutions is effectively more sensitive to gamma radiation than solid state. Current knowledge shows that polymeric materials are more sensitive to gamma radiation when solubilized in halogenated solvents [34]. The halogens are well-known to have large cross section for interaction with gamma radiation.

The main results obtained on irradiated P3HT devices were a significant improvement in conductivity with increasing gamma irradiation dose. Polythiophenes irradiated with gamma radiation go to a polaronic state and then stabilized for a bipolaronic and neutral state of the chain, where they remain in the oxidized state. Undoubtedly, the result enables the P3HT as radiation sensor and it leads to a great leap regarding the use of OLEDs and OFETs devices in the space area. However, the order of radiation dose used on P3HT (kGy) is very high for using in personal dosimetry (order of ten grays), for example.

In contrast, studies of MEH-PPV with gamma radiation at this order of dose have shown significant results compatible with personal dosimetry area. However, the results were limited to the use of the polymer in solution, due to the effect being dependent on the solvent. In other words, the effect is indirect: the radiation breaks the solvent chain and the radicals derived from solvent attack break the polymer chain. The attack occurs at the vinylene, breaking the double bond and leading to the conjugation break displayed as blue shift in optical measurements. This experimental result has been corroborated by theoretical studies and the attack mechanism on vinylene is well-established [35]. Figure 13 shows MEHPPV after ionizing radiation interaction.

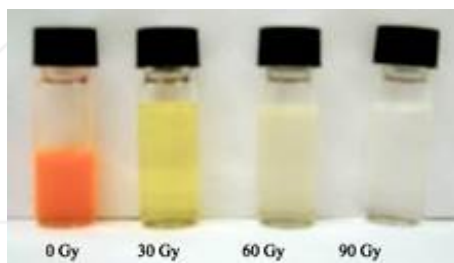


Figure 13. MEHPPV nonirradiated (0Gy) and irradiated at 30, 60, and 90Gy doses of gamma radiation.

The principal disadvantage of MEH-PPV in the interaction with the gamma radiation is its limitation of use in optoelectronic devices due to the effect of this range of dose not included the utilization in film. Moreover, with the breaking of the chain and the conjugation length,

the MEH-PPV has not sufficient extension of conjugation for a good conduction of electrons and neither has any chain doping as P3HT, which is also a limiting factor for their use in optoelectronic devices. Thus, its use is limited as optical sensor radiation in solution and can not be reused. Recalling that, despite limited use, this type of sensor provided an important advance due to measurement method be cheaper and affordable than other types of detectors. Semiconductor detectors based in conjugated polymers do not need be cooled, the instrumentation used for reading is simple, and polymers are cheaper and easier to process.

3. Applications

In short, a radiation detector is a device used to track, detect, or identify high-energy particles or radiation from natural or artificial sources such as cosmic radiation, nuclear decay, particle accelerators, and X-rays.

Since it is not possible for a single detector to measure all types of radiation efficiently, various types of detectors made of different materials are used in the sensing of specific types of radiation. The main types of radiation detectors and applications are summarized in Table 1.

Instrument Types	Detection Principle	Applications
Gas-filled detectors	Ionization of air or other gases (ionization chambers).	Direct measurement of exposure or exposure rates.
	Ionization of gas with multiplication of electrons in detector (proportional counters and Geiger-Muller).	Detection of individual events, i.e., alpha or beta particles and secondary electrons, for measuring activity (in samples or on surfaces); detecting low intensities of X-rays or gamma radiation.
Scintillators	Light emission (solids).	Photons; energy spectrometry; e.g., NaI (Tl). Alpha particles; detection only (ZnS (Ag)).
	Light emission (liquid).	Detection of low-energy gamma and beta emitters, for measuring activity (in low-activity sources).
Semiconductor detectors	Ionization, excitation.	Detection of individual events (alpha and beta particles); e.g., diodes and silicon barrier detectors.
		Detection and energy measurement of photons or particles; primarily for laboratory use; gamma spectroscopy; X-rays; dosimeters; e.g., Germanium detectors.
Thermoluminescent detector (TLD)	Excitation of crystal; light release by heating.	Personal and environmental exposure monitoring.
Photographic film	Ionization of Ag Br.	Personal exposure monitoring.

Table 1. Instrument types and its applications.

Despite the variety of sensor devices, the demand for new materials that can detect ionizing radiation efficiently and at as low a cost as possible is essential to the development of this area. In this context, many other materials like polymeric semiconductors, for instance, have been target of research in the last years (section 2). They constitute promising materials for radiation sensing, although no polymeric device for radiation detection is still available for practical use at a large scale.

Unfortunately, the field lacks new sensor devices that are more practical, fast, and accurate for the maintenance and safety of human life in the natural environment as well as in the complex areas of modern civilization.

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