IoT 4211: Sensor Technology

Radiation Measurement

Active Detectors

- In many applications it is important to produce a signal that indicates the presence of ionizing radiation in real time. Such devices are classified as active detectors
- An **active detector** is a type of radiation detector that requires power to operate and actively measures radiation by generating an electrical signal in response to particle or radiation interactions. Active detectors are widely used because they provide real-time, continuous readings and are highly sensitive to various types of radiation.
- An **active detector** is a type of sensor or device that requires an external energy source to detect and measure the presence or properties of particles, radiation, or other signals. Active detectors generate a measurable signal in response to the interaction with particles or energy they detect, and they rely on power to operate.

Modes of Operation

Energy Deposition and Charge Liberation:

•When a charged particle (e.g., alpha, beta particles, or photons) passes through the detector material (gas or semiconductor), it ionizes the atoms or molecules in the material, releasing charge carriers (electrons and positive ions in a gas, or electron-hole pairs in a semiconductor).

•The energy of the particle is transferred to the material, and the energy deposition liberates a certain amount of charge, Q. This is a very fast process, typically occurring on the scale of nanoseconds or less.

2. Charge Collection via Electric Field:

•After the charge is liberated, the electric field established within the detector (typically by applying a bias voltage across the detector) causes the free charge carriers (electrons and ions or electron-hole pairs) to move.

- In gases, the electrons are attracted to the anode, while the positive ions move toward the cathode. In semiconductors, the electron-hole pairs move in response to the applied electric field.

3. **Current Pulse:**

•As the charge carriers move through the detector material, they constitute an electric current. The detector's response to the deposited energy can thus be modeled as a **momentary burst of current** that corresponds to the amount of charge liberated by the particle.

•The burst of current starts when the charged particle stops and releases its energy and continues until all the charge carriers have been collected. The duration of this current pulse depends on the time it takes for the carriers to traverse the detector and reach the electrodes, which typically ranges from nanoseconds to microseconds.

Modes of Operation

4. Signal Processing:

•The momentary current pulse is usually very short, so detectors often use amplifiers or signal processors to increase the signal and convert it into a measurable output. The **pulse height** of the current can be analyzed to give information about the energy deposited by the particle (and hence the type of radiation).

•Detectors may also use **time-to-amplitude conversion** or **pulse shape analysis** to improve the resolution and accuracy of measurements.

5. Modeling the Detector Response:

•The response of the detector to a single quantum of radiation or particle can be modeled as a brief **current pulse**. The key parameters that affect the pulse are the amount of charge liberated, the detector's material properties, and the applied electric field.

•The **rise time** of the current pulse is very short (on the order of nanoseconds), but the **decay time** depends on how quickly the charge carriers are collected, which can take longer depending on the type of detector material and the strength of the electric field.

Modes of Operation: Current Mode

- One way to provide an electrical signal from such a detector is to connect its output to an ammeter circuit with a slow response time.
- In current mode, the detector’s output is connected to an ammeter (or a similar device) that has a slow response time compared to the frequency of the current pulses. This means the ammeter doesn't register each individual pulse but rather averages them over time.
- If the time spacing between the current pulses is shorter than the response time of the ammeter, the ammeter cannot resolve the individual pulses. Instead, it averages the pulses, providing a steady current reading.The current measured by the ammeter is proportional to the mean rate of charge formation in the detector, which in turn is related to the rate at which radiation quanta are interacting with the detector material.
- This mode of operation is called current mode, and many of the common detector types can be operated in this way.

Modes of Operation: Integrating Mode

- As ionizing radiation interacts with the detector, it generates current pulses (in gas detectors, semiconductor detectors, or scintillation detectors).The total current generated during the exposure time is accumulated by integrating the current over the duration of the exposure.
- Instead of measuring instantaneous values of current or voltage (as in current mode), in integration mode, the output signal is **integrated over time**.
- The detector's output is connected to an integrator circuit that sums the charge generated over the entire period of exposure. At the end of the exposure time, the integrator outputs the total amount of accumulated charge, typically displayed as a voltage or measured as **total charge (Coulombs)**.

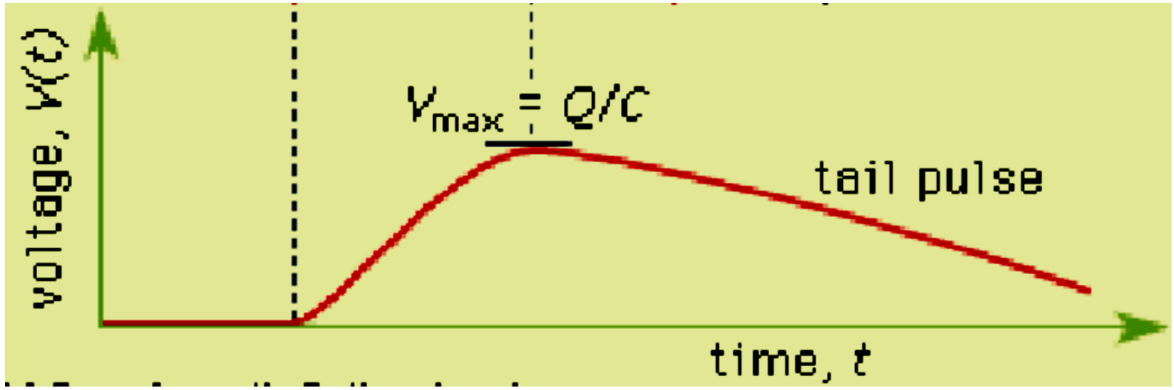
Mathematically, the total charge $Q_{total} = \int I(t)dt$

Where, I(t) is the current as a function of time, and the integral sums the total charge over the time of exposure.

- The result from this integration is a measure of the total exposure to radiation (often expressed in terms of Coulombs or Gray for dose). This value reflects the cumulative effect of all the ionizing events occurring over the exposure time. The total accumulated charge can then be used to determine the total radiation dose if the detector's efficiency and the type of radiation are known.

Modes of Operation: Pulse Mode

- a separate electrical pulse is generated for each individual radiation quantum that interacts in the detector.
- The detector output may be connected to a measuring circuit.



Counting System

- **Counting system:** In simple counting systems, the objective is to record the number of pulses that occur over a given measurement time.

- A common method is to employ an electronic unit known as an integral discriminator to count only those pulses that are larger than a preset amplitude.

- Alternatively, a differential discriminator (also known as a single-channel analyzer) will select only those pulses whose amplitudes lie within a preset window between a given minimum and maximum value.

Spectroscopy System

- **Spectroscopy system:** In many types of detectors, the charge Q and thus the amplitude of the signal pulse is proportional to the energy deposited by the incident radiation.

- Therefore, an important set of measurement systems are based on recording not only the number of pulses but also their distribution in amplitude.

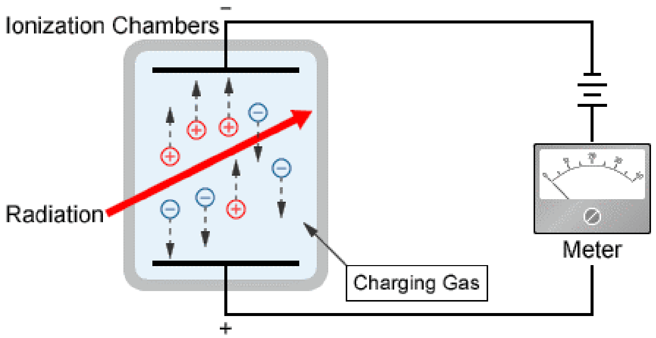
- They are known as spectroscopy systems, and their main application is to determine the energy distribution of the radiation that is incident on the detector.

Active Detector: Gas-filled Detector

A gas-filled detector is a type of radiation detector that uses a gas as the medium for detecting ionizing radiation. When ionizing radiation (such as alpha particles, beta particles, or gamma rays) passes through the gas, it interacts with the gas atoms, ionizing them and creating charged particles (ions and electrons). These ions are collected by electrodes in the detector, producing an electrical signal that can be measured. Gas-filled detectors are widely used in various applications, including nuclear radiation monitoring, particle physics experiments, and medical imaging, due to their relatively simple design and ability to detect a wide range of radiation types.

Gas-filled Detector: Ion Chambers

- An ion chamber is a device in which two electrodes are arranged on opposite sides of a gas-filled volume.
- By applying a voltage difference between the two electrodes, an electric field is created within the gas.
- The ion pairs formed by incident radiation experience a force due to this electric field, with the positive ions drifting toward the cathode and the electrons toward the anode.
- The motion of these charges constitutes an electric current that can be measured in an external circuit.
- Ion chambers are frequently operated as current-mode devices.



Gas-filled Detector: Proportional Counter

A Proportional Counter is a type of gas-filled detector used for detecting and measuring ionizing radiation. It operates on the principle of gas ionization, where the energy deposited by ionizing radiation in the gas generates charge carriers (electrons and ions). Unlike simpler gas detectors (like ionization chambers or Geiger-Müller counters), a proportional counter is specifically designed to produce an output signal (pulse) that is proportional to the energy deposited by the incoming radiation.

Gas-filled Detector: Proportional Counter

Gas Chamber:The detector consists of a sealed chamber filled with a gas mixture, commonly argon or neon, often mixed with a small amount of a quenching gas such as methane or carbon dioxide.The type of gas used affects the detector's sensitivity, energy resolution, and detection efficiency.

Anode and Cathode:The detector has two electrodes: an anode (positive) and a cathode (negative). The anode is usually a thin wire, and the cathode is often a cylindrical shell surrounding the anode.A voltage is applied between these electrodes, creating the electric field necessary for the collection of charge carriers.

High Voltage Supply:The proportional counter operates at moderate to high voltages (typically a few hundred to a thousand volts) that ensure ionization events.

Gas-filled Detector: Proportional Counter

Ionization of Gas: When ionizing radiation (such as alpha, beta, or gamma radiation) enters the proportional counter, it interacts with the gas atoms inside the detector, causing ionization — meaning it knocks electrons off gas molecules, creating ion pairs (electrons and positively charged ions).

Gas Amplification: The proportional counter operates in a specific voltage range where the collected ions and electrons undergo gas amplification. In this range, the electric field between the anode (positive electrode) and cathode (negative electrode) is strong enough to accelerate the electrons produced by the initial ionization, causing them to ionize other gas molecules, resulting in an avalanche of secondary electrons.

Proportionality of Pulse: The key feature of a proportional counter is that the size of the resulting pulse is proportional to the energy deposited by the radiation. The more energy the radiation deposits in the gas, the larger the pulse. The magnitude of the pulse is directly related to the number of ion pairs generated in the gas, which in turn is proportional to the amount of energy the radiation has deposited in the detector.

Pulse Collection: The charge carriers (electrons and ions) are collected by the anode and cathode electrodes, and the resulting current is amplified and counted. Each pulse corresponds to a single interaction of radiation with the detector. The output pulse can be analyzed in terms of both the number of pulses (to determine the rate of radiation events) and the pulse height (to determine the energy of the radiation).

Gas-filled Detector: Geiger-Müller counters

Geiger-Müller Tube: The central component of the GM counter is the Geiger-Müller tube itself, which consists of a thin metal wire (the anode) running through the center of a hollow cylindrical cathode (the outer casing). The tube is filled with a low-pressure gas (often argon, neon, or helium, mixed with a small percentage of a quenching gas).The anode is positively charged, and the cathode is negatively charged, creating the electric field needed for ionization and amplification.

High Voltage Power Supply: The GM tube requires a high voltage supply (between 300V and 900V) to maintain the electric field within the tube, which is necessary for the gas multiplication process.

Electronics: After the pulse is generated, it is processed by electronics (such as a pulse counter or amplifier). The electronics count the pulses, which are directly proportional to the number of ionizing radiation events detected. The counter may also display the count rate in terms of counts per minute (CPM) or counts per second (CPS).

Display: The output can be displayed digitally or on an analog meter, showing the number of detected radiation events. Some advanced GM counters may also show the count rate, which is the frequency of detected pulses over a given period.

Gas-filled Detector: Geiger-Müller counters

Ionization: When ionizing radiation (alpha, beta, or gamma) enters the Geiger-Müller tube, it interacts with the gas inside the tube, ionizing the gas atoms (i.e., knocking electrons off the gas molecules). This creates ion pairs: positive ions and free electrons.

Gas Amplification: The GM counter operates at a high voltage (typically between 300 to 900 volts). The voltage applied between the anode (central wire) and cathode (the outer cylindrical casing) creates a strong electric field. When the initial ionization occurs, the electrons created are accelerated by the electric field toward the anode. As the electrons move toward the anode, they gain enough energy to ionize other gas molecules, creating more electrons and positive ions. This process is called gas multiplication, and it results in a cascade of ionizations, leading to a large number of charge carriers (electrons and ions) being collected at the electrodes.

Gas-filled Detector: Geiger-Müller counters

Pulse Generation: The gas amplification process produces a large pulse of current. This pulse is of nearly the same size regardless of the amount of energy deposited by the radiation. Thus, in a GM counter, the output signal is essentially a count of radiation events rather than a measurement of their energy. Each ionizing event produces a single pulse that is collected, counted, and measured. The number of pulses is used to determine the radiation intensity (i.e., the count rate), but the energy of the radiation is not directly inferred from the pulse size.

Quenching: After an ionization event, the gas must return to its neutral state so it can detect subsequent radiation events. A quenching gas (such as methane, carbon dioxide, or halogen gases) is often added to the gas mixture in the tube. This gas helps to stop the ionization cascade and resets the gas to its original state, preventing continuous discharges or afterpulsing (spurious pulses after the main ionization event).Quenching is necessary to ensure that each pulse is discrete and does not interfere with subsequent pulses.

Semiconductor Detector

A semiconductor detector is a type of radiation detector that uses a semiconductor material to directly convert the energy from ionizing radiation into an electrical signal. These detectors operate on the principle of ionization in a semiconductor, typically silicon (Si) or germanium (Ge), and they offer several advantages over traditional gas-filled or scintillation detectors, including high resolution and precise energy measurement.

Neutron Detector

- The general principle of detecting neutrons involves a two-step process. First, the neutron must interact in the detector to form charged particles.

- Second, the detector must then produce an output signal based on the energy deposited by these charged particles.

Slow-neutron Detector

- One of the common detectors for slow neutrons is a proportional tube filled with boron trifluoride (BF_3) gas.

- Some incident neutrons interact with the boron-10 in the gas, producing two charged particles with a combined energy of 2.3 MeV.

- These particles leave a trail of ion pairs in the gas, and a pulse develops in the normal manner as in any proportional counter.

- Boron trifluoride performs as an acceptable proportional gas only at pressures of less than one atmosphere

- Alternatively, a conventional proportional gas can be used, and the boron can be present in the form of a solid layer deposited in the inner surface of the tube.

Slow-neutron Detector

- Proportional counters filled with helium-3 also are based on a neutron interaction in the gas that produces charged particles. In this case, the Q-value of 0.76 MeV imparts this energy to the particles formed in the reaction.

- Helium works well as a proportional gas even at high pressure; thus helium-3 proportional tubes filled to 20 atmospheres.

Fast-neutron Detector

- One method used to surround the detector with a material that effectively moderates or slows down the fast neutrons.

- For example, a polyethylene layer with a thickness of 20 to 30 cm will cause some incident fast neutrons to scatter many times from the hydrogen nuclei that are present, giving up energy in the process.

- A fraction of these moderated neutrons may then diffuse to the detector as slow neutrons with a high interaction probability.

Fast-neutron Detector

- The preferred conversion reaction for the direct detection of fast neutrons tends to be the elastic-scattering interaction.

- The resulting recoil nuclei can absorb a significant fraction of the original neutron energy in a single scattering and then deposit that energy in a manner similar to that of any other charged particle.

- The scattered neutron, now with a lower energy, may either escape from the detector or possibly interact again elsewhere in its volume.

- The most common scattering target is hydrogen, and a fast neutron can transfer up to all its energy in a single collision with a hydrogen nucleus.