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by Richard Wotiz (USA)

Ionization Detectors

It's time for a look inside a curious type of sensor that's used to bridge the gap between electricity and particle physics. This article covers a family of devices that measures ionizing radiation.

Welcome back to Embedded Unveiled! This month we'll journey inside an unusual type of sensor that's used to bridge the gap between electricity and particle physics. There are many types of detectors that use the principle of ionization to measure a variety of physical or chemical phenomena. I'll take a look at one family of devices that measures ionizing radiation. Then I'll peek inside an ionization smoke alarm to see how it works in the presence of varying amounts of smoke. Don't worry, no buildings were harmed in the creation of this column!

First, here's a quick lesson on the physics behind an ionization detector. There are many methods of producing ions, both naturally occurring (such as lightning), and man-made (such as a particle accelerator). A positive ion is created when an atom or molecule loses an electron, giving it a net positive charge. The negatively charged free electron can then combine with another atom or molecule, creating a negative ion. Since opposite charges attract, positive ions and either negative ions or free electrons in close proximity will be drawn together and recombine, neutralizing each other. The ionization detector works by creating an electric field between a pair of electrodes that attracts these charged particles before they recombine, causing a current to flow.

CATCHING RAYS

Three related types of ionization detectors are used for measuring radioactivity. They all use a sealed metal container with a pair of electrodes. Often the container itself acts as one of the electrodes. There is also a window that's transparent to the particular type of radiation

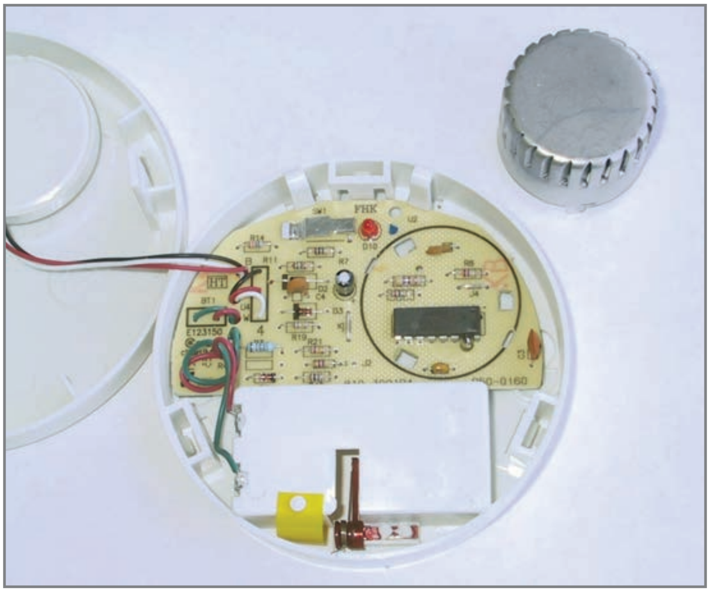

Photo 1—The inside of a smoke detector with the ionization chamber removed. You can see the test button at the top of the printed circuit board (PCB) and the alarm sounder mounted to the top cover at the far left.

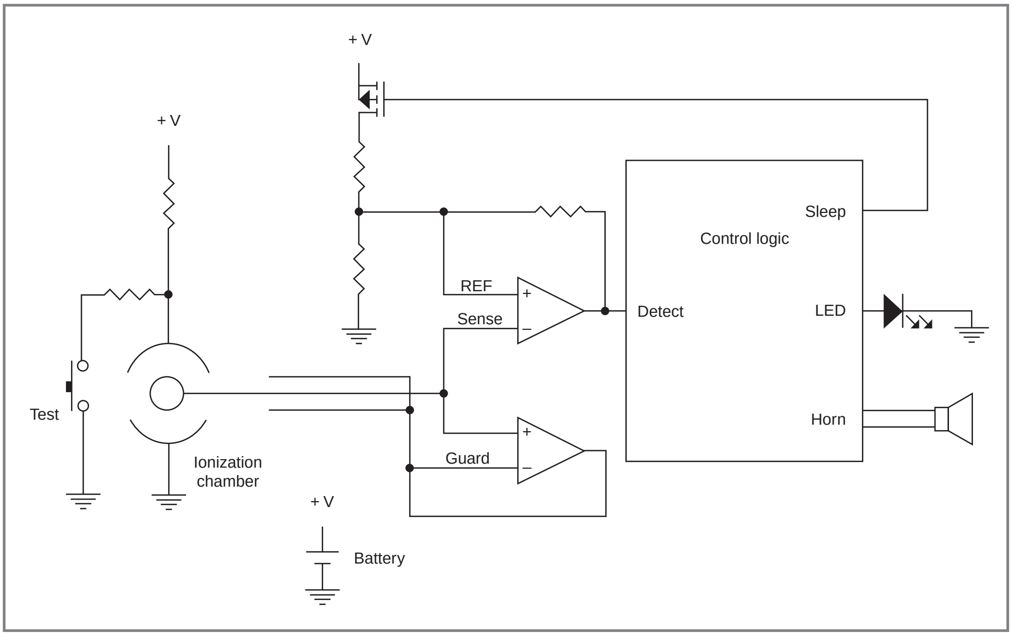

Figure 1—The key components of the smoke detector. The sense input circuitry and control logic are contained within a single integrated circuit.

being measured. When a radioactive particle enters the container, it may collide with an atom of the gas that is inside. If the particle has enough energy, it will knock off an electron, ionizing the atom.

The key difference between the detector types is the range of electrode voltages. The simplest, but also the least sensitive, is the ionization chamber. It can operate on a voltage as low as a few volts. When ions are created in the chamber, the electric field between the electrodes will draw positive ions to the negative electrode and negative ions to the positive electrode. This movement, called drift, is proportional to the strength of the electric field. It is a slow phenomenon, typically less than 1 m/s. The drift causes a current to flow that's proportionate to the number of ions reaching the electrodes. The current can be very small, typically in the picoampere range, so you need a sensitive amplifier with extremely high input impedance. This is not difficult with modern FETs, but in earlier days, you'd need an expensive electrometer to get a meaningful signal.

The second type of detector is known as a proportional counter. The physical construction is similar to an ionization chamber, but it uses a higher voltage. This causes an avalanche effect, where a free electron is accelerated enough by the electric field to knock off more electrons from additional atoms. The avalanche eventually dies out on its own. This results in an amplification effect, which produces an output signal that's proportional to both the electrode voltage and the energy of the radioactive particle that started the process.

The last type, which is the most sensitive, is the Geiger-Müller tube. Like the proportional counter, it depends on the avalanche effect. But the voltage is set high enough so that the entire gas volume in the container will ionize with each incoming particle. Therefore, the output signal does not depend on the energy of the incoming particle; it can only be used to count particles. This process results in the familiar clicking sound produced by a Geiger counter that has an audio output.

Ionization chambers are commonly used in smoke alarms that you can buy for your home. But instead of measuring external radiation, the chamber contains a weak radioactive source to create its own stream of ions. It's also open to the outside air, so smoke can enter and affect the movement of the ions. This changes the current flow through the chamber's electrodes, which sounds the alarm.

SMOKE ALARMS

The first battery-powered smoke alarms appeared on the market in 1969, but they didn't come into widespread use in the U.S. until the following decade.[1] That's when the national building codes first included a requirement for smoke alarms in new homes, and Underwriters Laboratories first developed standards for them. As a result, manufacturing of smoke alarms jumped from an estimated 50,000 units in 1971 to more than one million by 1974, increasing to more than 10 million annually by the mid-1980s.[2]

Photo 1 shows the inside of a typical ionization smoke alarm. I was quite surprised when I first opened one up; I was expecting to see a bit more complexity. It turns out almost all of the circuitry is contained in a single IC, in this case a Microchip Technology RE46C152 low-power CMOS ionization-type smoke detector IC. Figure 1 shows a simplified schematic of the unit. The ionization chamber has

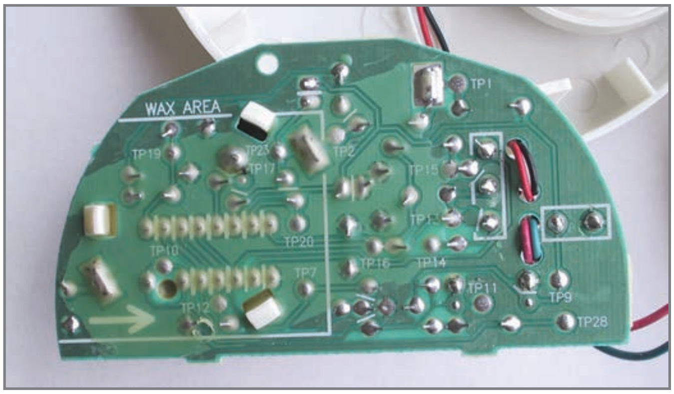

Photo 2—The bottom of the PCB. Part of the board is covered in beeswax to protect the high impedance paths from contamination that could lead to excessive leakage current.

three electrodes, which enables the sense signal to be measured independently from the chamber supply current. The chamber's output impedance is high enough that even the slightest leakage current will shift its voltage level. To combat this, the adjacent pins on both sides of the IC's sense input are guard pins, which are outputs driven to the same level as the input. This minimizes leakage across the IC package. The input pin itself isn't connected to the printed circuit board (PCB); rather it is bent upward and soldered directly to the chamber's sense pin. If you look closely near the bottom right corner of the IC in Photo 1 you can see a solder blob where I unsoldered the pin from the chamber. The rest of the circuitry isn't quite as high impedance as the sense input, but it can still be affected by humidity or dust settling on the PCB. Photo 2 shows the bottom of the board covered in beeswax, which is much less expensive than a conformal coating, but still does the job.

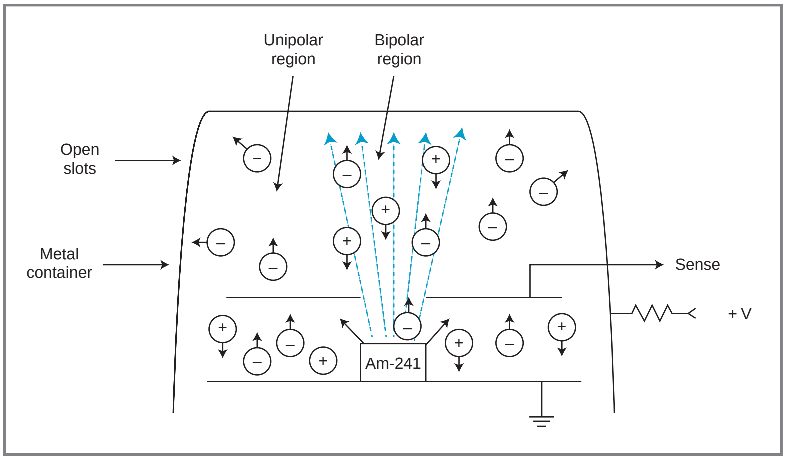

Figure 2—The ionization chamber contains a small radiation source to ionize the air inside. The ions are drawn to the opposite polarity electrode, causing a small current to flow.

IONIZATION CHAMBER

Figure 2 is a diagram of the ionization chamber. The radioactive source is specified on a label on the smoke alarm as 0.9 microcuries (µCi) of Americium-241 (Am-241), which emits a constant stream of alpha particles. The particles have an energy of 5.486×10^6 electron volts (eV), which will travel up to 4 cm in air. Alpha particles are the largest and slowest type of radioactive particle and can be stopped by a sheet of paper. But, their large size also gives them enough mass to impart significant energy to whatever they may bump into, which makes them extremely dangerous to come in contact with. I was careful to take proper safety precautions when removing the chamber from the PCB for the photo. I then replaced it right away without disassembling it any further.

The maximum current that can flow through the chamber is given by:[3]

$$I_S = e\left(\frac{E_m}{E_i}\right) F\, Q\, S, \text{ where:}$$

I_S = chamber saturation current (amps)

e = charge of an electron = 1.6×10^{-19} C

E_m = ionizing particle energy = 5.486×10^6 eV

E_i = ion pair formation energy $\approx$ 14 eV for air (nitrogen and oxygen)

F = efficiency factor of radioactive source (assume 1.0)

$$Q = \text{ionizing particles per second per curie} = \frac{3.7 \times 10^{10}\ \frac{\text{s}}{}}{\text{Ci}}$$

S = source activity = 0.9×10^{-6} Ci

This gives a saturation current of 2.1 nA. The chamber is supplied from the 9-V battery through a 1-M resistor, so the chamber is being operated at saturation. I used an efficiency factor (F) of 1.0, which assumes that there isn't any filtering of the alpha particles. It's possible that the source includes a thin layer of gold foil to reduce the particle energy, which would reduce F, but I don't have access to the proper equipment to find out. In any case, that would only reduce the saturation current, which wouldn't change how the chamber operates.

There are two basic configurations for an ionization chamber. In a bipolar chamber all of the air is ionized, so both positive and negative ions are present throughout its volume. A unipolar chamber is designed so the radiation source only ionizes part of the air. The rest of the chamber will only contain ions of a single polarity that have been pulled there by the electric field. A space-charge region, acting as a boundary layer, will form between the two areas. This will enable ions to travel to the unipolar area at a relatively constant rate if the chamber is being operated at saturation. The term "unipolar" may seem a bit misleading since the chamber does contain both positive and negative ions, but it refers to the fact that part of the chamber farthest from the radiation source only contains ions with one polarity. In both chamber types, ions will be attracted to uncharged smoke particles if they are present and will attach themselves to the smoke. The charged smoke particles move much more slowly than the ions, which will cause a reduction in current flow in the chamber. The unipolar chamber is more sensitive to smoke density, and less affected by environmental changes and air movement.[4]

The geometry of the chamber I examined appears to be designed to have a unipolar region, since the sense electrode partially shields the alpha source so it's not exposed to the entire chamber volume. In operation, no appreciable current flows to the sense input, so the sense electrode will take on an intermediate voltage between the other two electrode voltages. When smoke enters the chamber, it will have a much greater effect on the unipolar region, since its supply of ions is limited by the ion flow across the boundary layer. This will cause a larger voltage drop between the sense electrode and the positively charged metal container. The sense voltage will decrease by an amount that's approximately proportional to the smoke concentration times the average particle size, eventually triggering the alarm.

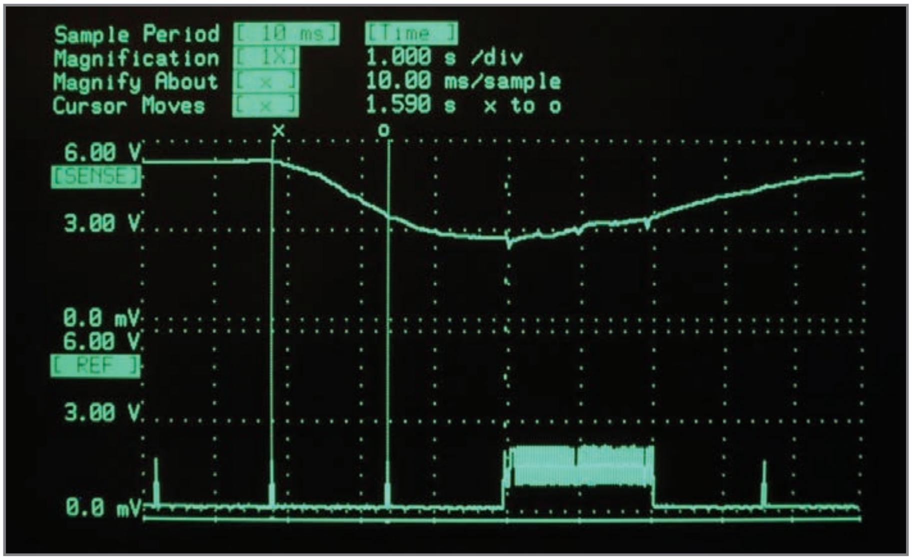

Photo 3—The system's response to a small puff of smoke. The scope's sampling rate is too slow for the REF amplitude to be accurate, but you can see the periodic sampling every 1.59 s until SENSE drops low enough to trigger the alarm.

After leaving the unit in the refrigerator overnight, I found the Sense signal had dropped slightly to 5.07 V from its nominal room-temperature value of 5.30 V. Next, I subjected the alarm to the high-humidity environment of a hot shower, but I didn't see any measurable change in the output. I didn't have any practical way to test it at varying pressures—I could only imagine trying to explain to airport security why I was carrying a disassembled smoke alarm and some test equipment onto an airplane!

Residential smoke alarms like the one I tested are calibrated at the factory and are designed to stay within specifications for their 10-year operating lifetime. Their performance is specified by the UL217 standard (see Resources). I noticed that the units I examined each had a different resistor value installed at a particular location on the PCB that affected the REF voltage level. That's to compensate for unit-to-unit variations in the ionization chamber's output. Smoke alarms designed for non-residential buildings are subject to more stringent accuracy and testing specifications, both at manufacture and during their lifetime, and are evaluated using the UL268 standard. They're required to have regular testing to confirm that their sensitivity is within range, rather than just a simple Go/No-go functional test.[5] To get this level of accuracy and stability, the alarms have two identical ionization chambers. One is exposed to smoke and the other is protected so smoke can't enter. The alarm is triggered when the voltage difference between the two chambers exceeds a set threshold. Any environmental or lifetime-related drift

TESTING

At this point, I wanted to try out the smoke alarm for myself. I opened one up that still had its ionization chamber intact, disconnected the piezo beeper, and connected some wires to the Guard and REF pins. That way I could look at the detection comparator signals while it was operating. Since the Guard pin is driven to the same level as the Sense input, it enables me to monitor the chamber's voltage without putting any additional loading on its high-impedance output. Photo 3 shows the system responding to a small puff of smoke. The comparator status is checked about every 1.5 s until smoke is detected. Then it's repeatedly checked until the smoke clears. While the alarm is sounding, the LED blinks once per second. You can see small blips on the Sense signal as the battery voltage dips slightly with each blink. You'll also see a corresponding gap in the REF signal, since the comparator isn't checked during the blink to avoid a false reading.

Photo 4 is a closeup of the alarm trigger point. You can see the REF signal more clearly as it gets enabled by the Sleep signal to take a measurement about every 40 ms. The smoke alarm also has a hush feature that temporarily silences a false alarm. It works by reducing the REF signal by about a volt, which makes the alarm less sensitive without entirely disabling it.

I wanted to see how sensitive the ionization chamber was to changing environmental conditions, since it can be affected by temperature, humidity, and atmospheric pressure.

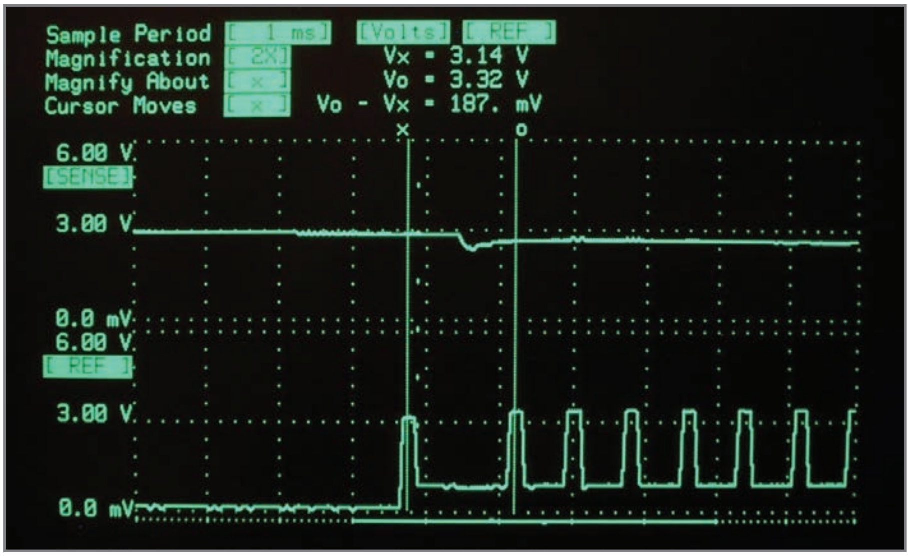

Photo 4—A closeup of the alarm trigger point. Note the 187-mV hysteresis on the REF signal under the cursors. The horizontal scale is 50 ms per division.

will affect both chambers equally and will only have a minimal effect on the alarm's sensitivity.

I hope you've enjoyed this journey into the world of smoke and physics. I certainly have a new appreciation for all the research that's gone into fire detection in the past 50 years, as well as what really happens when I hear that unmistakable beeping sound.

Richard Wotiz has been taking products apart ever since he was old enough to pick up a soldering iron. He's been helping others put them back together since 1991, when he started his design consulting business. Richard specializes in hardware and software for consumer products and children's toys. He can be reached at rw601@spiraltap.com.

REFERENCES

[1] R. Bukowski et al., "Performance of Home Smoke Alarms: Analysis of the Response of Several Available Technologies in Residential Fire Settings," *NIST Technical Note 1455-1*, National Institute of Standards and Technology, 2008.

[2] R. and G. Mulholland, "Smoke Detector Design and Smoke Properties," *NBS Technical Note 973*, National Bureau of Standards, 1978.

[3] C. Litton, "Optimizing Ionization-Type Smoke Detectors," *Fire Technology*, Vol. 15 No. 1, 1979.

[4] A. Scheidweiler, "Physical Aspects of Ionization Chamber Measurement Techniques (Unipolar and Bipolar Chambers)," Fire Detection for Life Safety, Proceedings of a Symposium, National Research Council (U.S.) Committee on Fire Research, 1975.

[5] National Fire Protection Association, "NFPA 72: National Fire Alarm and Signaling Code," 2010.

RESOURCES

R&E International, a Subsidiary of Microchip Technology, Inc., "RE46C152: CMOS Ionization Smoke Detector ASIC with Interconnect, Timer Mode, and Tone Select" Product Specification, 2009, ww1.microchip.com/downloads/en/DeviceDoc/22175A.pdf.

Underwriters Laboratories, "UL217: Single and Multiple Station Smoke Alarms," 2006.

———, "UL268: Smoke Detectors for Fire Alarm Systems," 2009.

SOURCE

RE46C152 CMOS Smoke detector IC
Microchip Technology, Inc. | www.microchip.com

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