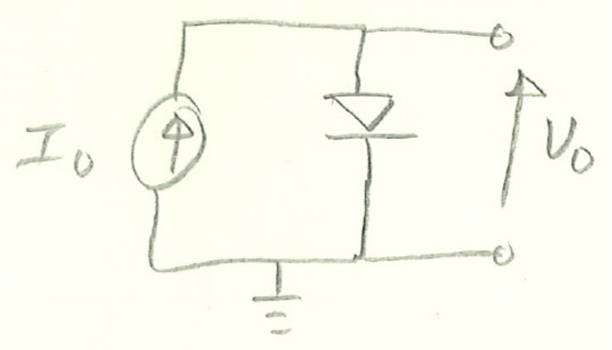
Lecture 11/21/24

Temperature Sensors (Continued)

a. Thermodiodes and thermotransistors

(1) Thermodiode temperature sensing

Consider this thermodiode circuit:



$$I_o = I_s\left[e^{\lambda q V_o / k_B T} - 1\right]$$

Or: $V_o = \frac{k_B T}{q} ln\left(\frac{I_o}{I_s} + 1\right)$, for $\lambda = 1$

$\frac{k_B T}{q} = V_T$ is the thermal voltage

k_B is the Boltzmann's constant (1.38×10^{-23} J/K)

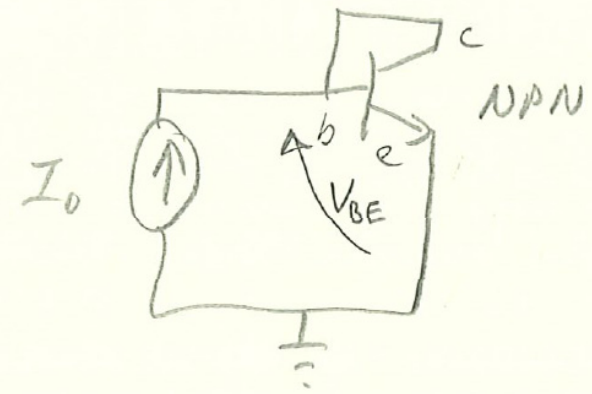
q is electronic charge (1.60×10^{-19} C)

I_s is the diode reverse saturation current

For this circuit, set I_o to a constant current and then measure V_o to "determine" temperature. However, I_s increases as temperature increases.

(2) Thermotransistor temperature sensing

Consider this thermotransistor circuit:



$$V_{BE} = V_T ln\left(\frac{I_c}{I_{co}}\right)$$

$I_{co} = A_E J_S$ → saturation current (I_S)

A_E → emitter junction area

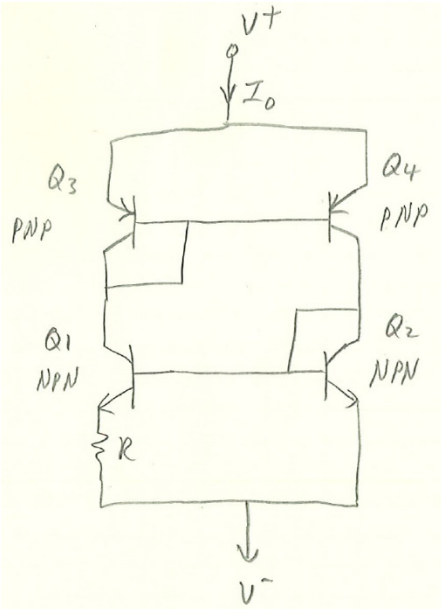
J_S → saturation current density

$\frac{k_B T}{q} = V_T$ → the thermal voltage, as before

However, the emitter junction area (A_E) can vary over the process tolerance range. Therefore, a better thermotransistor temperature measurement circuit is typically used.

(3) PTAT temperature measurement sensor

PTAT stands for "Proportional to Absolute Temperature." It is a better thermotransistor circuit for measuring temperature:



$$I_o \approx \frac{2k_BT}{qR} ln\left(\frac{A_{E2}}{A_{E1}}\right)$$

Notice that the current is a function of the ratio of two emitter junction areas, which should track equally over the fabrication tolerance range. Therefore, error due to fabrication tolerances is largely eliminated.

Therefore, PTAT circuits are commonly used to measure temperature on microdevices.

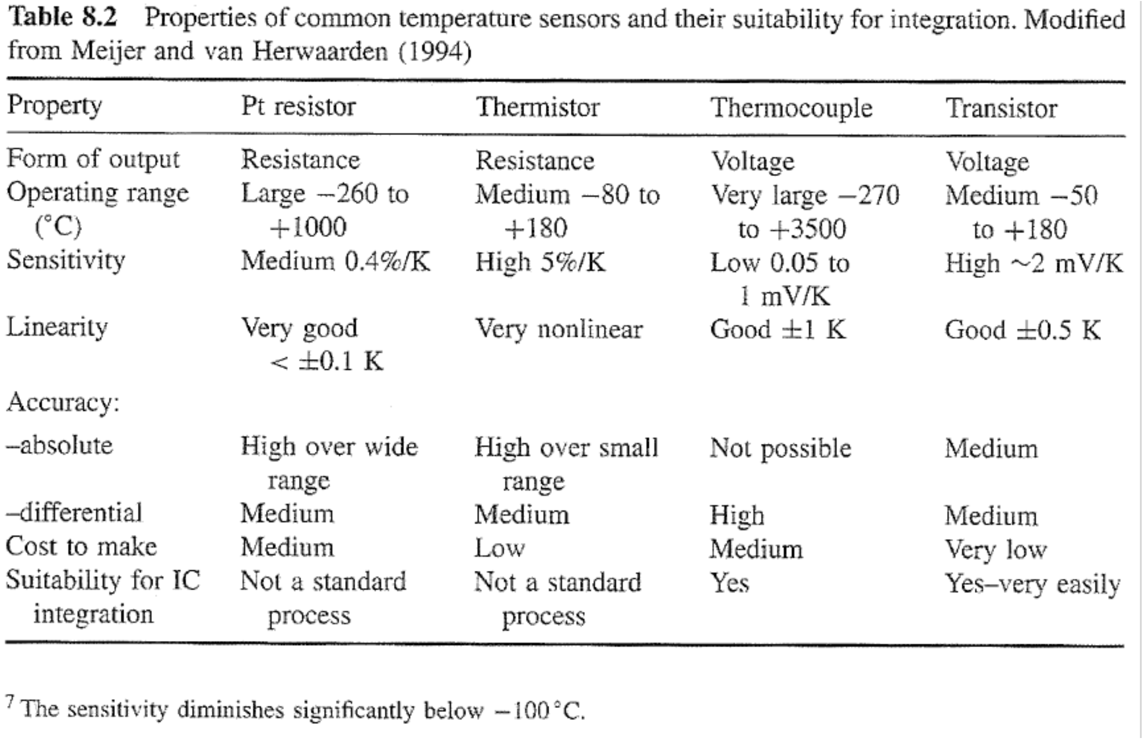


Table 8.2 Properties of common temperature sensors and their suitability for integration. Modified from Meijer and van Herwaarden (1994)

Property	Pt resistor	Thermistor	Thermocouple	Transistor
Form of output	Resistance	Resistance	Voltage	Voltage
Operating range (°C)	Large −260 to +1000	Medium −80 to +180	Very large −270 to +3500	Medium −50 to +180
Sensitivity	Medium 0.4%/K	High 5%/K	Low 0.05 to 1 mV/K	High ~2 mV/K
Linearity	Very good < ±0.1 K	Very nonlinear	Good ±1 K	Good ±0.5 K
Accuracy:				
–absolute	High over wide range	High over small range	Not possible	Medium
–differential	Medium	Medium	High	Medium
Cost to make	Medium	Low	Medium	Very low
Suitability for IC integration	Not a standard process	Not a standard process	Yes	Yes–very easily

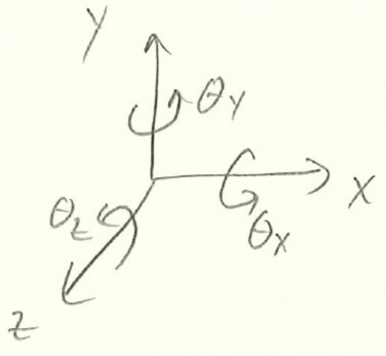
[7] The sensitivity diminishes significantly below −100 °C.

Chemical Sensors (Introduction)

1) The difficulty of chemical sensing

a. Consider inertial motion sensing

3 axes: 6 things to measure: 3 orthogonal translational accelerations and 3 orthogonal angular rates:



MEMS accelerometers → usually not affected by rotation.

MEMS gyroscopes → can be affected by large translational accelerations: can possibly use the accelerometers to compensate for this.

Temperature sensitivities → use an integrated temperature sensor (such as the PTAT) to compensate.

Drift errors over time → use a fixed reference to compensate (direction of gravity, earth's magnetic field, GPS, etc.).

Seal the unit in a hermetic package to isolate it from moisture, dust, etc. in the operating environment.

There are not many other possible environmental parameters that affect these sensors.

b. Consider a CO detector in your home

The atmospheric chemistry approximately consists of: 78% N_2, 21% O_2, 0.9% Ar, ~1% H_2O vapor, 0.03% CO_2, 0.018% Ne. 0.005% He, …

A quality CO sensor needs to not only respond to CO with high sensitivity, but to also be insensitive to all other gases present.

The sensor also needs to be insensitive to temperature, dust, vibration, light, biologicals, air pressure, liquids, etc. In other words, compared to inertial sensors, it requires substantially greater exposure to the environment, and therefore it must be much more highly selective in what it is sensitive to. This characteristic greatly complicates the realization of quality chemical sensors.

Chemical Sensors (Architectures)

2) Introduction

The "*analyte*" is the chemical we desire to sense.

A chemical sensor consists of two parts:

(1) Chemically sensitive layer

With one type of chemically sensitive layer, it reacts with the analyte, resulting in a corresponding change in some electrochemical property, such as resistivity or electrical permittivity. With a second type, the chemically sensitive layer produces a change in a mechanical property, such as mass or strain.

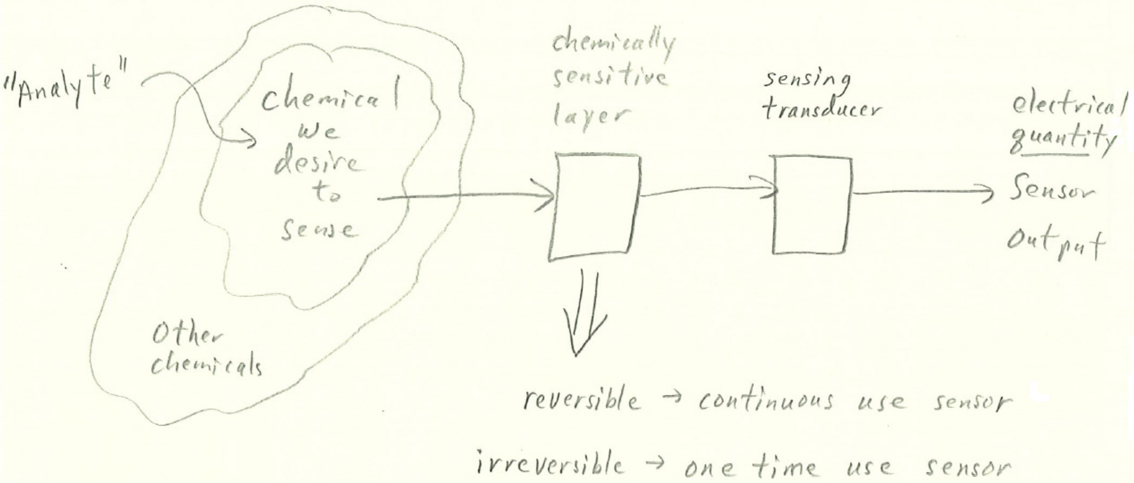
Sometimes the chemical process of the chemically sensitive layer is reversible, yielding a continuous use sensor. Example: a relative humidity sensor.

Sometimes the chemical process of the chemically sensitive layer is irreversible, yielding a one-time use sensor. Example: a disposable blood glucose sensor.

(2) Sensing transducer

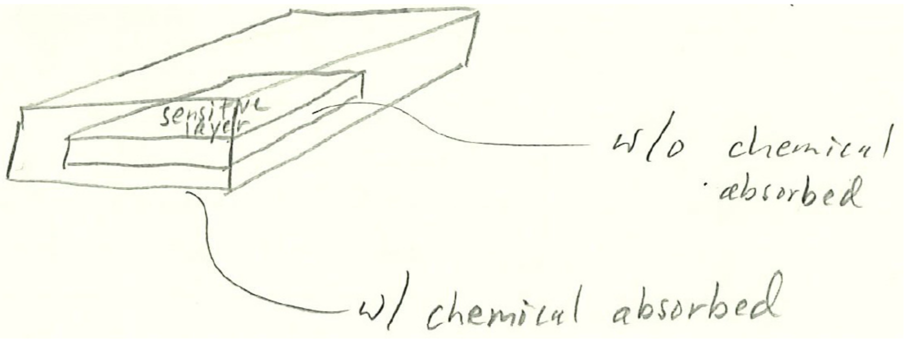
With one type of chemically sensitive layer, the sensing transducer converts the change in an electrochemical property into a change in an electrical parameter (resistance, capacitance, voltage, etc.). With a second type of chemically sensitive layer, it converts the change in a mechanical property into a corresponding change in an electrical property (resistance, frequency, voltage, etc.)

Consider this diagram:

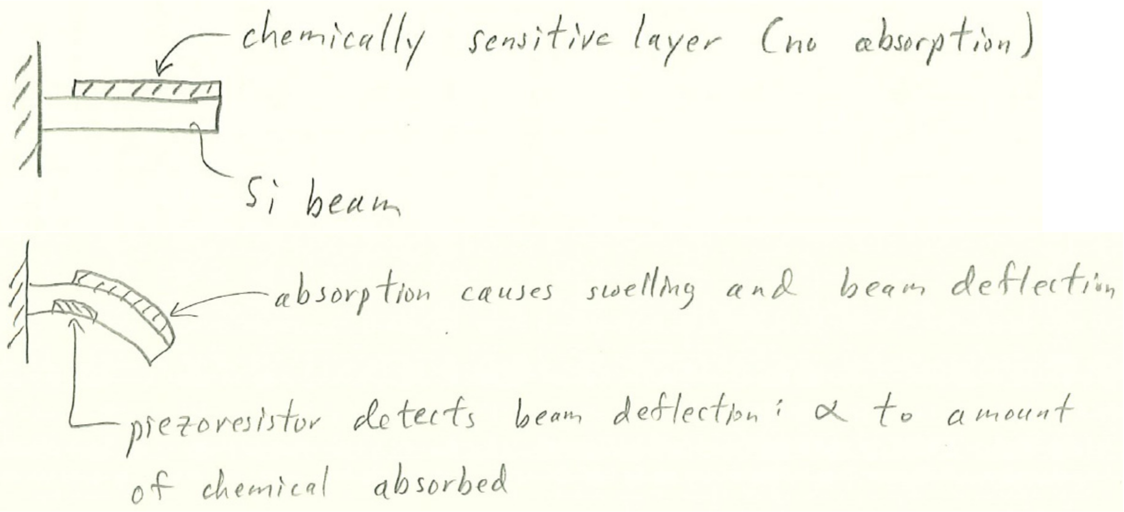


3) Chemical sensor architecture 1: chemically sensitive layer produces a mechanical strain

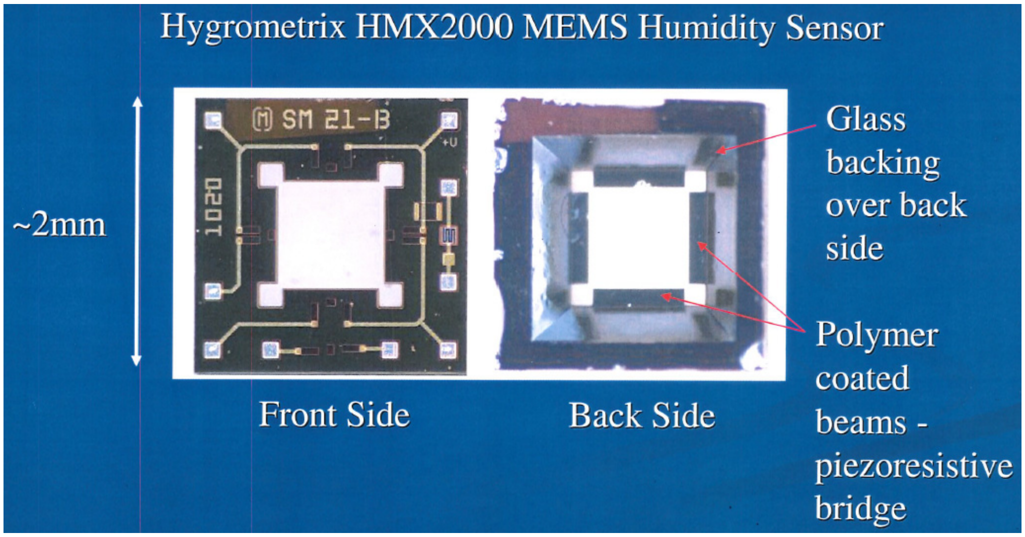
The chemical absorption by the chemically sensitive layer causes the layer to volumetrically change (example: swelling).



The chemically sensitive layer can be attached to a beam that deflects as the layer swells. The deflection can be detected using piezoresistors.



Consider the HMX2000 humidity sensor:



Hygrometrix HMX2000 MEMS Humidity Sensor

~2mm

Front Side

Back Side

Glass backing over back side

Polymer coated beams - piezoresistive bridge

4) Chemical sensor architecture 2: conductimetric devices

The sensed gas interacts with the chemically sensitive layer and changes the electrical conductance (resistivity).

The typical sensor is the Taguchi-type tin-oxide sensor.

This sensor type uses a joule heater to heat the tin-oxide layer to ~300 – 400°C (typically).

This elevated temperature does three beneficial things:

(1) It improves sensor specificity.
(2) It results in a faster response time.
(3) Above 100°C, humidity effects are eliminated.

The sensor response metric is G_s/G_o, where:

G_s is the sensor's conductance for a specific gas of fixed concentration.

G_o is the sensor's conductance in air.

Different tin-oxide compounds have different specificities:

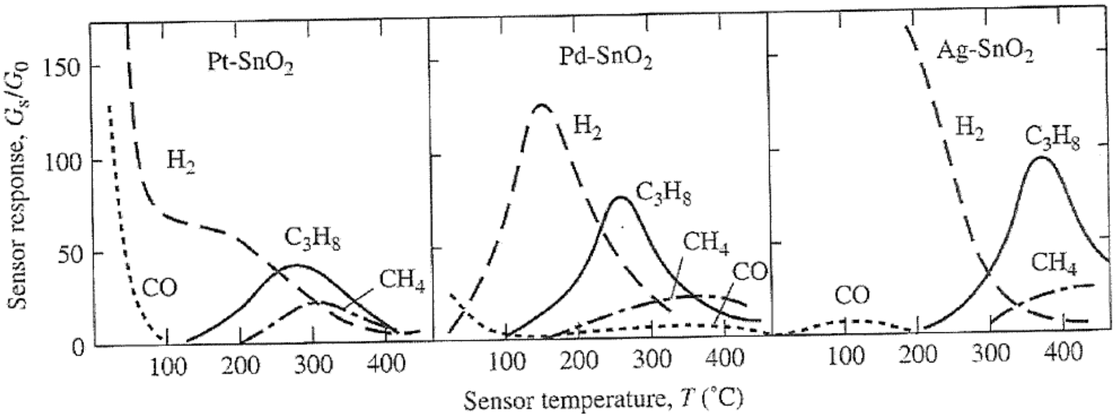


Figure 8.52 Variation of the response of three doped tin oxide gas sensors with temperature for four different gases. Adapted from Yamazoe *et al.* (1983)

This is how those sensors work:

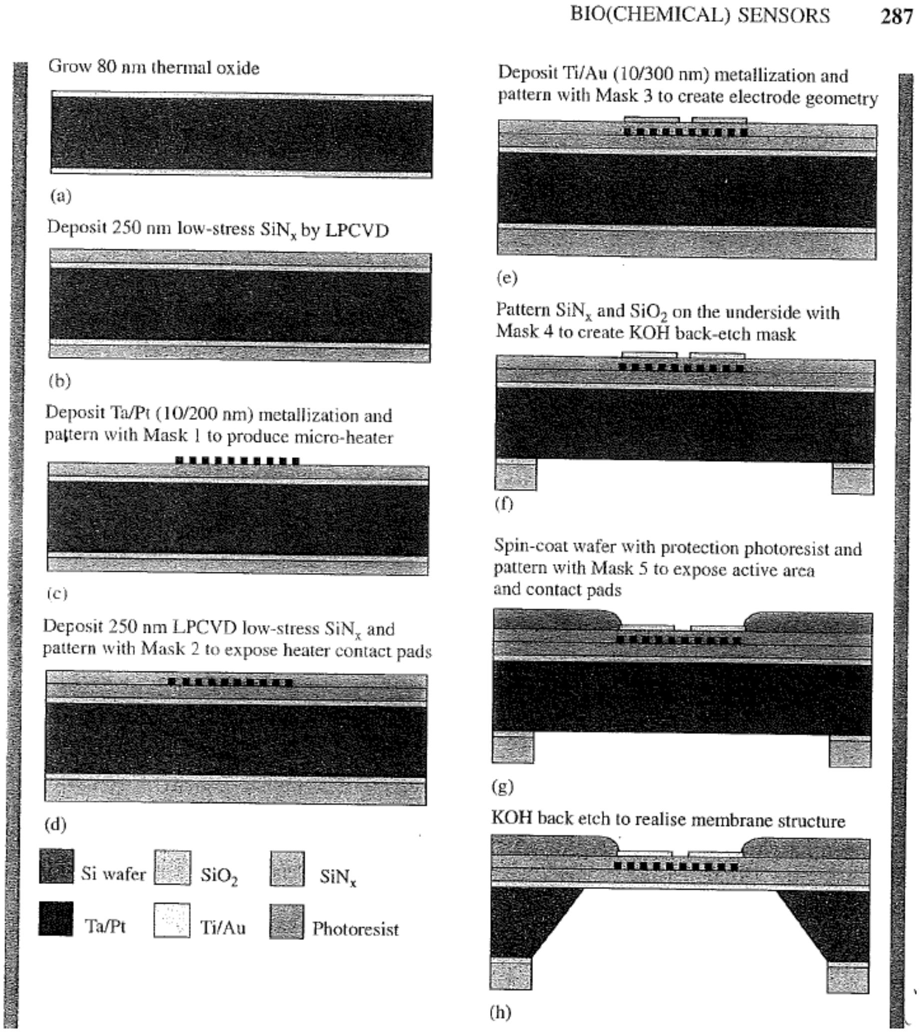
(1) The heated tin-oxide attracts O_2 molecules that abstract an electron from the tin oxide → chemisorption.

(2) The analyte gas molecule reacts with the chemisorbed O_2 molecule, releasing it and electrons in the tin-oxide material:

Example: $CO + O_{ad}^{-}(SnO_{2x}) \rightarrow CO_2 + SnO_{2x} + e^{-}$

(3) The released electrons result in increased electron carrier density and increased electrical conductivity.

Conductimetric sensors can be manufactured with MEMS technology:



On-chip heaters are realized on diaphragms or bridge structures.

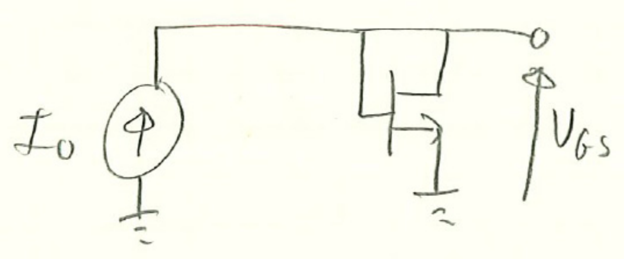
The chemically sensitive layer is placed on top of the heater (that would be step (i) above) and cured/processed.

5) Chemical sensor architecture 3: potentiometric devices

This sensor is a MOSFET transistor with a gate made with a gas-sensitive catalytic metal.

This gate material/structure allows the gas to flow through the gate electrode and affect the dielectric material beneath it.

Consider this circuit:



I_o is a controlled, constant current applied to the circuit. The resulting V_{GS} is then measured.

Observe that $V_{GS} = V_{DS}$: $i_D = I_o \approx \frac{1}{2}\mu_o C_{ox}\frac{W}{L}(V_{GS} - V_T)^2$

The presence of the specific gas changes V_T, the threshold voltage, thereby changing V_{GS} for a constant I_o: if V_T↑, then V_{GS}↑.

Ionizing radiation has a similar effect in the V_T of a MOSFET, where charges get trapped in the oxide layer under the gate due to the ionizing radiation. So, a MOSFET can be used to detect an ionizing radiation event.