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Direct Detection of Alpha Particles with Solid-State Electronics

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Alpha-particle sources are widely used in industrial and medical applications. Such applications include smoke detectors, static charge eliminators, and radiation therapy.[1,2] This paper is concerned with the detection of alpha particles. A number of techniques are known for the detection of alpha particles. Those techniques include the Geiger–Müller tube, the ZnS scintillator, the air-filled ionization chamber, and the spark chamber.[3,4] All the techniques that are currently known are based on the interaction of the ionizing radiation with matter. Charged particles, such as alpha particles, upon entering a medium (such as air), encounter many collisions with bound electrons and lose kinetic energy in the process. The atoms of the medium also become ionized, and a large number of free electrons are released inside the medium. The theory describing the interaction of ionizing radiation with matter is well known and includes formulas such as the Bethe-Bloch formula for the stopping power of matter[5] and formulas for calculating the range of the ionizing radiation in matter. Essentially, all the known techniques for the detection of alpha particles are based on detecting the presence of free electrons inside the medium. This paper presents a new technique for the detection of alpha particles that does not depend on the theory of the interaction of alpha particles with matter. Instead, the technique is based on the direct detection of the positive charge that is carried by the alpha particles. Furthermore, it is the objective of this paper to demonstrate that the direct detection of the charge carried by alpha particles can be done with a tiny and inexpensive component: a metal–oxide–semiconductor field-effect transistor (MOSFET).

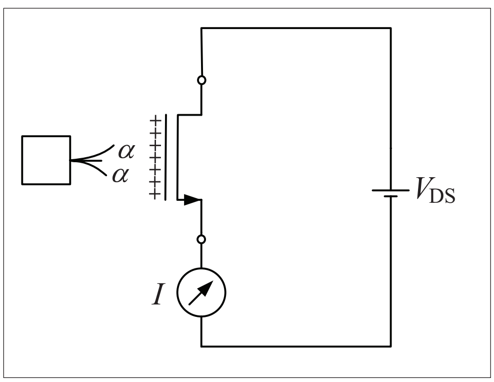

Fig. 1. Principle of operation of the MOSFET based alpha-particle detector. Alpha particles, upon reaching the gate terminal of the MOSFET, acquire free electrons from the metal and become helium atoms. Accordingly, the positive charge is transferred to the gate, and the MOSFET starts conducting a current *I* that is proportional to the charge on the gate. V_{DS} = drain-to-source voltage.

Figure 1 shows the principle of operation of the new alpha-particle detector that was assembled and tested by the authors. As shown, the alpha particles are allowed to strike directly the gate terminal of an n-channel MOSFET. Each alpha particle acquires free electrons from the metal electrode that is connected to the gate and becomes a helium atom. Accordingly, the positive charge is transferred to the gate terminal. The MOSFET is a transistor that is highly sensitive to the presence of a charge on the gate, and, in this case, it will respond to the presence of the positive charge on the gate. The presence of this charge allows the device to conduct current, where the current *I* is proportional to the charge on the gate, and hence proportional to the number of alpha particles that reach the gate per unit time.

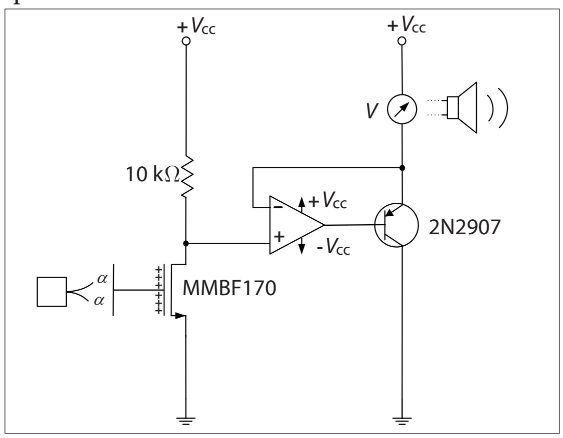

Fig. 2. Complete circuit of the alpha-particle detector. The circuit consists of an n-channel MOSFET plus interface electronics. V_{cc} = voltage at common collector.

It must be pointed out that beta particles (high-speed electrons) can also be detected using this technique; however, a p-channel MOSFET must be used (see "Detection of beta radiation" section).

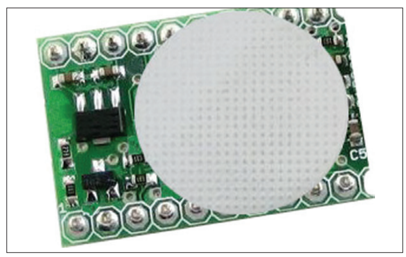

Fig. 3. Photo of the detector circuit. The circular component is the metal electrode that receives the incident alpha particles.

The MOSFET interface circuit

Although the current that is circulating in a MOSFET can be measured with desktop instruments, a small and inexpensive interface circuit was designed by the authors for the purpose of using such an interface circuit in a handheld detector. The MOSFET and its interface circuit are shown in Fig. 2. As shown, the gate terminal of the n-channel MOSFET (part no. MMBF170) is connected to a metal electrode that is exposed to an incoming stream of alpha particles. The drain terminal of the transistor is connected to a 10-kΩ pull-up resistor and is also connected to a high-impedance OpAmp in a voltage follower configuration. An optional PNP transistor can be inserted in the voltage follower circuit, as shown, for the purpose of driving a heavy load, such as an audio buzzer.

The circuit works as follows: when the alpha particles are not present, the MOSFET will be in the off state, and hence the input (and output) of the OpAmp will be high because of the presence of the pull-up resistor. Accordingly, the voltage present on the emitter terminal of the PNP transistor will be high (close to V_{cc}), and the voltmeter that is attached to that emitter will be reading approximately 0 V (as also shown in Fig. 2, an audio buzzer can be used in lieu of a voltmeter). When a stream of alpha particles is striking the gate terminal of the MOSFET, however, the MOSFET starts conducting current, and the voltage on the drain terminal drops. Due to the voltage follower circuit, that drain voltage also appears at the emitter terminal of the PNP transistor. The voltmeter now starts reading a voltage due to the lower voltage on the emitter terminal. That voltage will be proportional to the number of alpha particles that is striking the MOSFET per unit time. As shown in the figure, an audio buzzer can be used in lieu of the voltmeter for generating an audible signal when alpha particles are present.

Fig. 3 shows a photograph of the new detector. The circular component is the metal electrode that is connected to the gate of the MOSFET.

Theory of the MOSFET alpha-particle detector

Determination of the turn-on conditions of the MOSFET

See Appendix A.[6]

Current supplied by the alpha-particle source

The alpha-particle source that was used to test the new detector described above is a commercially available foil that contains approximately 5 μCi of ^{241}Am (with a half-life of 432 yr[7]).[8] Five microcuries results in approximately 185,000 emissions per second.[9] Since each alpha particle contains two protons, the equivalent of 370,000 positive electron charges will be emitted from the source each second. It should be pointed out that ^{241}Am sources also emit gamma and X rays in addition to the alpha particles, but the detector is not sensitive to photonic radiation. Since the alpha-particle source is a flat film, it is isotropic (i.e., alpha particles are emitted in all directions). In the present application, it was determined that approximately 10–20% of the emitted alpha particles will reach the electrode. The minimum steady-state current that is expected to reach the gate of the MOSFET will be therefore given by

$$I = \frac{\Delta Q}{\Delta t} = \frac{370{,}000 \times 0.1 \times 1.6 \times 10^{-19}}{1} = 5.92 \times 10^{-15}\ \text{A}\ \left(\frac{\text{Charge}}{\text{Time}}\right). \quad (1)$$

This value exceeds the value of the turn-on current that was derived above. A direct substitution with this value of I into Eq. (8) from Appendix A[6] gives a steady-state gate-source voltage VGS that is substantially high (larger than 10 V). A simplified cross-sectional drawing of the n-channel MOSFET is shown in Fig. 4.[10]

Calculation of the operating points of the MOSFET

See Appendix B.[6]

Sensitivity of the MOSFET detector

As shown above, the present detector is sensitive to an alpha-particle current of a few thousand particles per second. It is therefore comparable in its sensitivity to detectors based on the air-filled ionization chamber. It is less sensitive, however, than the Geiger–Müller tube, which can detect the presence of a few tens of particles. The advantages of the present detector by comparison with the other known techniques are the very small size and the low cost.

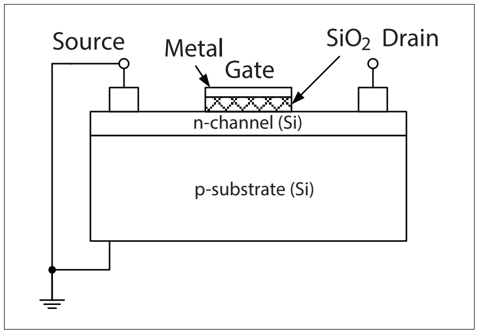

Fig. 4. Simplified cross-sectional drawing of the n-channel MOSFET.

Experimental results

Output voltage of the detector as a function of distance from the alpha-particle source

The foil containing the ^{241}Am was placed at various distances from the detection circuit, and the output voltage of the circuit (see Fig. 2) was observed. Figure 5 shows the output voltage as a function of distance. As expected, the MOSFET is fully on (and hence the output voltage is equal to 6 V) when the detector is within a distance of about 2 cm from the alpha-particle source. At larger distances, the output voltage drops very quickly to 0 V, as a diminishing number of alpha particles reach the detector. (The lower number of alpha particles that reach the detector is due to both absorption by the intervening atmosphere and the change in the solid angle subtended by the gate electrode; the first effect, however, is much more significant in the present detection technique). The range of the alpha particles in air can be calculated using the Bethe-Bloch formula for the stopping power of matter (see Appendix C[6]). It is approximately 4 cm for the 5.5-MeV alpha particles emitted by ^{241}Am.

Testing with smoke as a screening mechanism for alpha particles

Smoke, as is well known, can block the propagation of alpha particles. Smoke was released in the vicinity of the detector, and the smoke obscuration was measured with a commercially available laser-based smoke detector as described in Ref. 11. Figure 6 shows the output voltage of the detector as a function of the smoke obscuration. It should be pointed out that the distance between the alpha-particle source and the detector was 5 mm in this test.

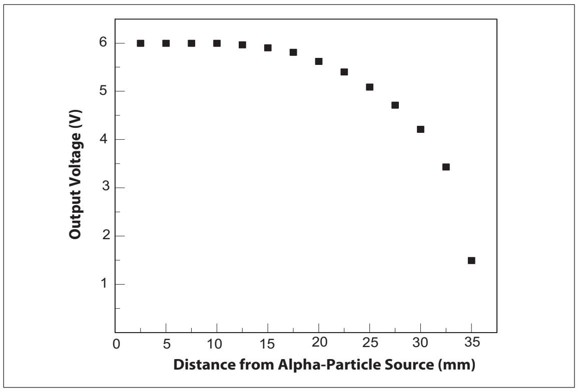

Fig. 5. Output voltage of the detection circuit as a function of distance from the alpha-particle source.

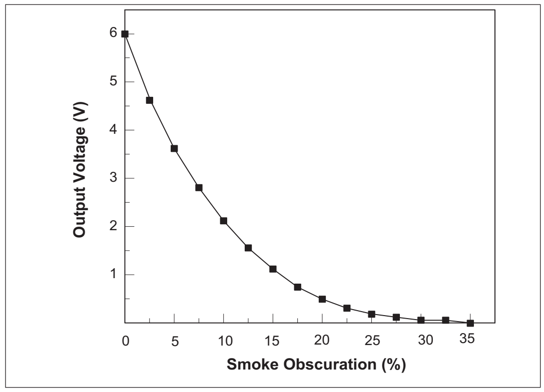

Fig. 6. Output voltage of the detection circuit as a function of the smoke obscuration (%).

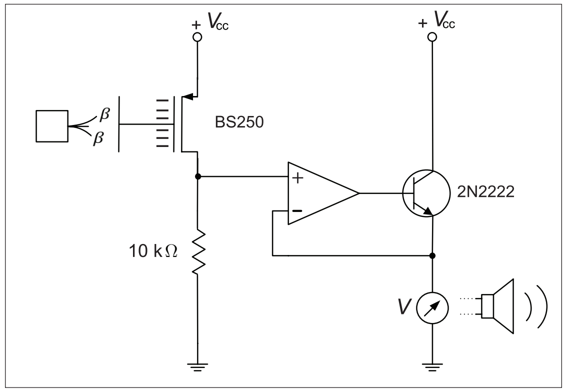

Fig. 7. Complete circuit of the beta-particle detector. The circuit consists of a p-channel MOSFET plus interface electronics.

Effect of the ambient temperature

See Appendix D.[6]

Detection of beta radiation

The circuit in Fig. 2 was modified to enable the detection of beta radiation (high-speed electrons). The modified circuit is shown in Fig. 7. As shown in the circuit schematic, the n-channel MOSFET was replaced by a p-channel MOSFET. The source terminal of the MOSFET is connected to a voltage follower consisting of an OpAmp and a NPN transistor. The principle of operation of the circuit is the same as the circuit shown in Fig. 2. This detector was tested with a beta-particle source that is available in the laboratories of the physics department. The beta-particle source consists of a silicon disk in which tritium is embedded. The results of the testing are very similar to the results reported above for alpha-particle radiation.

Conclusion

The alpha-particle detection method presented in this paper can be taught to physics students as an alternative method to the techniques that are based on the interaction of ionizing radiation with matter. The new detector presented here is characterized by a very small size, simple circuitry, and low cost. Moreover, as shown above, this type of detector can be used for the detection of beta radiation or other types of charge-carrying radiation. Finally, it is worth mentioning that this circuit will be susceptible to damage by electrostatic discharge (ESD), and therefore precautionary measures against ESD should be taken when using this circuit.

Additional References

References 12–14 provide additional resources on instrumentation and measurement that the reader may find helpful in building and testing the new detector described in this paper.

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