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SEMICONDUCTOR COUNTING SYSTEM FOR
HIGH-RESOLUTION ALPHA-PARTICLE SPECTROSCOPY

R. N. Chanda and R. A. Deal

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BY

R. N. Chanda
R. A. Deal

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ABSTRACT

A high-resolution, semiconductor, alpha-particle, spectroscopy system has been designed. The system employs a low-noise FET charge-sensitive pre-amplifier having a noise contribution of 0.77 keV silicon equivalent at 0 pf and a noise-capacitance slope of 0.028 keV/pf of input capacitance. The detector remains in constant vacuum during changing of samples, and provision is made for cooling both the detector and first stage of the preamplifier. When operated at 0°C, resolutions of < 12 keV FWHM have been obtained for 5.8 MeV α -particles.

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I. INTRODUCTION

Recent advances in semiconductor detector fabrication techniques and low-noise amplification systems have made the semiconductor counting system an important tool for alpha-particle spectroscopy. Present obtainable resolutions (≈ 0.2 percent) are approaching those of the magnetic spectrometers (≈ 0.1 percent), and (with proper attention to the stability and linearity of the electronics) α -energies determined from semiconductor systems can be measured with an accuracy better than one part in ten thousand. Although magnetic spectrometers still hold the edge in resolution, this gap is continually narrowing; further advances in semiconductor technology will undoubtedly see resolution progress from the present 11 to 12 keV FWHM toward the statistical limit of 5 to 6 keV^[1] FWHM for 6 MeV α -particles.

The simplicity and versatility of semiconductor detectors make them a natural laboratory tool. A semiconductor system has been designed which is capable of alpha resolutions of < 12 keV FWHM at 5.8 MeV; yet this semiconductor system can be used equally well as a routine assaying instrument or as part of an α - γ coincidence spectrometer.

II. SYSTEM DESCRIPTION

The system described below (Figure 1) utilizes a surface-barrier detector mounted in a chamber so designed that the detector remains cooled, in a constant vacuum, and at full bias while changing samples. A field-effect transistor (FET) charge-sensitive preamplifier and low-noise amplifier and biased amplifier are used in conjunction with a 1024-channel pulse-height analyzer for amplification and pulse-height analysis.

Fig. 1 Block diagram of semiconductor counting system.

1. Cryostat and Chamber

The main portion of the alpha-particle spectrometer (Figure 2) consists of two brass cylinders which house the detector and internal portions of the low-noise preamplifier. The detector and internal preamplifier components are mounted on a 3/8-inch-diameter copper rod (cold finger) which extends to the top of the chamber where it is connected to a 10-liter cold-storage dewar (Linde CR-10)^[2]. This arrangement permits cooling of the detector as well as certain internal preamplifier components. The field-effect transistors used in the preamplifier are mounted just above the detector on a brass ring which is insulated from the copper rod with teflon. This feature was included so that the detector could be cooled to near liquid nitrogen temperature ($\approx 78^\circ\text{K}$) and at the same time maintain the FET's at or near 140°K where their inherent

No engineering drawings exist - B.F. Boardman 8/7/67

Fig. 2 Alpha-particle spectrometer with cutaway view showing internal preamplifier components, detector, and sample holder.

noise is minimum^[3]. Since the detectors are currently operated at $\approx 0^{\circ}\text{C}$, the brass ring is "heat sunked" to the cold finger so that the FET's and detector are at the same temperature. Internal components are electrically connected to external components through a nine-pin "Kovar" seal in the upper chamber wall.

A four-inch gate valve^[4] separates the upper sections of the chamber from the removable sample holder. The detector thus remains in a constant vacuum, free from light, and at full bias during sample insertion or removal. The upper two brass sections and gate valve are bolted together and sealed with neoprene "O"-ring gaskets while the sample holder is held in position only by the external air pressure. The sample rests in a cup mounted on a 1/4-inch-diameter steel rod. The rod slides through a brass plate where a vacuum seal is maintained with "O"-ring gaskets. Since oil vapors may be detrimental to silicon surface-barrier detectors, a Zeolite filter is used in the pump-out line.

2. Chamber Operation

The portion of the chamber above the gate valve is maintained at fore-pump pressure ($\approx 10^{-3}$ Torr). Sample insertion or removal is accomplished via the four-inch gate valve. Because of its small volume (2 to 3 cc), the sample holder can be evacuated and integrated with the rest of the system in less than one minute. The vac-ion pump was included in the system for cooling to much lower temperatures (ie, liquid nitrogen) where a higher vacuum would be useful in providing maximum insulation. For temperatures down to $\approx 238^{\circ}\text{K}$ (dry ice), the fore-pump is adequate and the vac-ion pump is not used.

Optimum performance has been obtained with the cryostat operated at $\approx 0^{\circ}\text{C}$. The detector and FET's were originally cooled with crushed ice, but later a small refrigeration unit was installed which circulates an alcohol cooling solution in the cold-storage dewar. This permits longer counts without maintenance and also allows the temperature to be varied to determine optimum operating conditions for each detector. Temperature stability with the unit is $\pm 0.2^{\circ}\text{C}$.

3. Detectors

The present detector mount consists of a micro-dot fitting imbedded in the end of the copper coldfinger. Silicon surface-barrier detectors of 25-mm^2 active area with micro-dot connectors have been used. The detectors were purchased from ORTEC^[5] and have factory quoted resolutions of 17 to 20 keV FWHM for

the Am-241, 5.48 MeV line. Resistivities are in the order of $10^3 \Omega\text{-cm}$, and the diodes are operated at applied reverse bias voltages of 100 to 200 volts.

4. Electronics

The alpha-particle spectrometer system employs a low-noise charge-sensitive preamplifier (Figure 3) which is a DC-coupled version of one developed earlier in this laboratory^[3]. The charge gain of the preamplifier is set by the 0.5-pf feedback capacitor. In addition, the preamplifier has provisions for paralleling FET's in the input stage which results in considerable improvement in the resolution-versus-capacitance slope over the single FET preamplifier^[3]. The unit described here employs four FET's giving a noise contribution of 0.77 keV silicon equivalent at 0 pf plus 0.028 keV/pf of input capacitance (including detector and stray capacitance to ground). Input capacitance is minimized by keeping the lead from the detector to the preamplifier first stage as short as possible. In this case, the lead is approximately one inch long.

Fig. 3 Simplified schematic diagram of FET preamplifier.

DC coupling the preamplifier-amplifier chain allows the use of pole-zero correction techniques in the pulse-shaping section of the main amplifier. The result is output pulses which return to the base line with no appreciable

undershoot. In the preamplifier system (shown schematically in Figure 4), pole-zero correction is obtained by adjusting R_2 and R_3 such that $R_1 C_1 = R_2 C_2$ and $\frac{R_2 R_3}{R_2 + R_3} C_2 = R_5 C_5$. The resistor, R_5 , is placed in parallel with the input capacitor in the 1.6 μ -sec first-differentiator section of the main amplifier.

Fig. 4 Block diagram of preamplifier and main amplifier showing pertinent resistors and capacitors used for pole-zero correction.

Since the cryostat is generally operated at temperatures of 0°C or less, detector leakage currents are low enough (a few nano amperes) that a large bias resistor ($10^9 \Omega$) can be used (see Figure 1). For room-temperature operation, detector-leakage currents are higher, and one should lower this value to $10^8 \Omega$ or less (depending upon the properties of the detector).

The preamplifier output is fed through a Tennelec TC-200 main amplifier having single 1.6 μ -sec differentiating and integrating time constants. After further amplification with a Tennelec TC-250 biased amplifier, the pulses are analyzed on a Nuclear Data 1024-channel pulse-height analyzer.

For routine monitoring while taking data, and for noise measurements, provision is made for connecting a pulser^[6] into the preamplifier through a 0.5-pf test capacitor (Figure 1). A procedure for measuring noise has been adopted which measures the equivalent noise charge (ENC) of the system. For a given set of conditions (ie, detector in or out, amplifier gains set, etc) the RMS noise of the system (V_{noise}) is noted at the amplifier output with the pulser disconnected. Then the pulse height out of the amplifier (V_{out}) is measured for a given pulser amplitude (V_{in}). Using the following expression^[7] for equivalent noise charge,

$$ENC (\text{KeV, Silicon}) = 5.12 \times 10^{16} \frac{V_{in} \times V_{noise} \times C_{test}}{V_{out}}$$

and with voltages expressed in volts and C in farads, the noise of the system can be expressed in keV FWHM silicon equivalent. In this way, with the detector removed, the noise figure of 0.77 keV at 0 pf was obtained for the preamplifier (system noise in this case is equivalent to preamplifier noise since the noise generated by the TC-200 is negligible). For the 25-mm² detectors used in the spectrometer, typical noise figures are 4 to 5 keV silicon at room temperature and 2.4 to 2.8 keV silicon at 0°C.

For accurate energy determinations, the system nonlinearity is determined using a precision pulser designed by R. A. Coates of this laboratory^[8]. This pulser has an amplitude stability of several parts in 10⁵ for short runs (one to three minutes), and the linearity is good to several parts in 10⁵. An article by Black^[9] gives a complete discussion of linearity determinations and their application to precise energy measurements.

In an effort to minimize the effects of external noise, the AC input power is isolated with a two-stage quadruple-shielded isolation transformer^[10].

III. DISCUSSION OF RESULTS

At room temperature operation, resolutions of < 15 keV FWHM^[a] were obtained for detectors rated at ≤ 20 keV FWHM by the manufacturer. Cooling to $\approx 0^\circ\text{C}$ consistently gave resolutions of < 13 keV FWHM, and the best performance (11.9 keV FWHM) was obtained with a 920 Ω -cm resistivity device operated at 100-volt reverse bias at a detector temperature of -2°C (see Figure 5). The above performances have been obtained for six different diodes, all of which were rated at 17 to 20 keV FWHM. Counting times were in excess of 40 minutes duration with a peak height of at least 10,000 counts in the 5.80-MeV Cm-244 line. Count rates were the order of 1000 c/min at a source-to-crystal distance of 2 cm. Alpha sources were prepared by the evaporation and subsequent flaming of a TTA (thenoyltrifluoroacetone)-nuclide solution onto a platinum plate^[12]. The activity was confined to an area ≤ 4 mm diameter by a depression in the platinum plate made with a fire-polished glass rod.

It might be expected that chamber dimensions would influence the shape of the low-energy portion of α -spectra through scattering off metal surfaces. Before designing the counting chamber, a study was made in an effort to determine the effect, if any, of such scattering. Even when conditions for scattering were "optimized" by placing a one-inch-diameter metal cylinder between the source and detector, no perceptible effect was noted in the relative height of the low-energy tail. Nor was any detrimental effect observed in resolution or peak-to-valley ratios. For these reasons, no attempt was made to increase the dimensions of the chamber over those necessary to house the detector and electronics.

In addition to high resolutions, large peak-to-valley ratios and large peak-to-low-energy-tail ratios have also been achieved. Such ratios are particularly important when attempting to resolve low-intensity α -groups on the low-energy side of an intense α -line. In Figure 6 the 0.1 percent intensity line of Pu-240 is clearly resolved where the low-energy tail at this point (≈ 150 keV below the main peak) is 0.10 percent of the main peak intensity. In Figure 5 some evidence is seen for the line^[11] of 0.02 percent intensity in Cm-244 where the height of the tail at this point (≈ 150 keV below the main peak) is 0.11 percent.

[a] Quoted resolutions were obtained for the 5.80-MeV line of Cm-244 using standard "ORTEC" 25-mm² silicon surface-barrier detectors of ≈ 100 -micron depletion depth. Alpha-particle energies were taken from Reference 11.

Fig. 5 Alpha-particle spectrum of Cm^{244} with a resolution of 11.9 keV FWHM. Energies are shown in MeV with relative intensities in parentheses.

Fig. 6 Alpha-particle spectrum of Pu-240 showing clearly a line of 0.1 percent intensity at 5.014 MeV. Energies are shown in MeV with relative intensities in parentheses.

IV. CONCLUSION

The spectrometer described has been shown to be capable of alpha-particle resolutions of < 12 keV FWHM at 5.80 MeV. Although the spectrometer has been described only as a tool for singles experiments, the unit can readily be adapted for α - γ coincidence work by removing the gate valve and substituting an opaque plastic chamber in its place. With the source inside the plastic chamber, and with an external gamma-ray detector, coincidence measurements can be undertaken at either 90- or 180-degree orientations. In addition, the spectrometer is adaptable for conversion electron and β -spectra measurements merely by changing detectors.

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