D-MICROGEIGER: A MICROFABRICATED BETA-PARTICLE DETECTOR WITH DUAL CAVITIES FOR ENERGY SPECTROSCOPY

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ABSTRACT

This paper reports on micromachined Geiger counters fabricated from stacks of glass and Si wafers. As a beta particle passes through, a bias applied between two enclosed electrodes generates electron cascades in the gas between them. This results in a current pulse or "count". A single die of 2 cm^2 had 6 independent chambers ranging in size from 8X8 mm^2 to 1X3 mm^2. Helium and neon, which have different voltage bias requirements, were separately evaluated as background gases. In tests the device was found to detect incident beta particles from a Uranium-238, and calibrated ^{90}Sr, ^{60}Co, and ^{204}Tl sources, of 0.1-1 μCurie strength. In the D-microGeiger incident beta particles pass through two independent cavities that are separated by a glass barrier, which provides calibrated energy absorption. By comparing the counts in the two cavities, information about the energy of the radiation is determined. This provides an inherent ability to discern the chemical nature of the isotope, not just the presence of radiation.

I. INTRODUCTION

Environmental monitoring is emerging as a significant driver of microsystems technology. For applications ranging from industrial control to homeland security, there is a widespread need for microsystems that can provide a first alert for specific thresholds of various environmental variables ranging from pressure, temperature and humidity to the presence of toxic gases. Radiation sensors, for example, can be potentially used to detect the presence of "dirty" bombs, which are conventional explosive devices used to disperse radioactive material,.

Since a few radioactive materials emit X-rays, one possibility is to exploit X-ray detectors, which have benefited from solid-state technology in recent years [1, 2]. In addition, miniaturized gas-based X-ray detectors have been fabricated, which also determine the energy of these photons [3].

Unfortunately, most radioisotopes are not sources of X-rays, and the best way to detect most of the target species for dirty bombs is through their emission of beta particles. There are a wide variety of beta emitting isotopes, and the difference in emitted beta energy is considerable. Uranium-238 naturally decays into ^{234}Th and then ^{234m}Pa, emitting 0.8 MeV beta particles, which are essentially high energy electrons. Other possible dirty bomb ingredients include a number of beta sources, including ^{90}Sr, ^{60}Co and ^{204}Tl. The former is a particularly hazardous material, as it is easily absorbed into the human body, where it displaces calcium

in bone, remaining there with a radioactive half-life of 27 years. ^{90}Sr emits 0.546 MeV beta particles. ^{60}Co provides a range of beta particles, with a maximum energy of 0.314 MeV. ^{204}Tl produces a spectrum of beta particles with a maximum energy of 0.776 MeV.

Solid-state detectors for beta particles exist, but they are relatively large, with sizes on the order of 1 cm^2. They typically require cryogenic cooling to distinguish radiation type and energy, and are particularly susceptible to radiation damage [4,5,6]. Another type of device uses pixelated silicon structures at room temperature to provide spatial imaging of beta particle flux [7].

Geiger counters, however, are the preferred sensors for detecting beta radiation [1]. Conventional Geiger counters are toaster-sized devices, with an electrode pair in partial vacuum, biased at 500-1000 V. A thin window permits the entry of beta particles, which ionize the gas in the tube, resulting in avalanche breakdown, and registering individually as "counts" (Fig.1). These gas-based detectors are very reliable, temperature insensitive, require only simple circuitry, and measure over a much wider range of radiation species and energies. However, traditional Geiger counters do not *discriminate* between different radiative species, e.g. between medical waste and reactor by-products or benign and lethal isotopes. These detectors cannot discriminate beta particle energy.
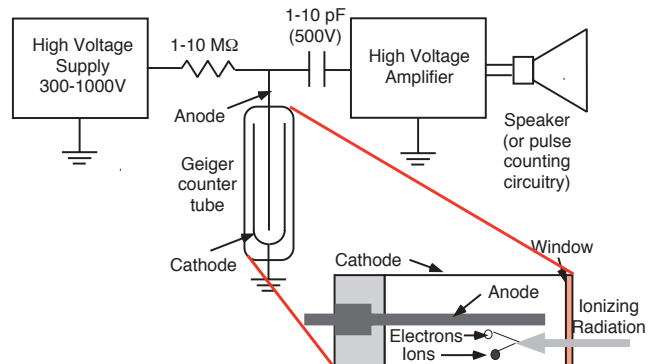

Fig. 1: Traditional Geiger counters utilize a tube under partial vacuum, and a high voltage supply applied through a resistor to a small capacitor.

In contrast the D-microGeiger, sized presently from 9-64 mm^2, and 2.5 mm thick, provides room temperature operation and measures beta particle interaction with the background gas in two independent cavities. This differential measurement allows energy spectroscopy, giving the potential field user vital real time information

conventional Geiger counters cannot. The D-microGeiger expands on the concept of a simpler device reported by us in the recent past [9] that did not provide energy discrimination.

II. DEVICE CONCEPTS AND OPERATION

The basic microGeiger (Fig. 2) has a square chamber with a central cathode and a peripheral anode. The region proximal to the cathode has a weak field and is called the drift region, whereas that adjacent to the anode is the high-field amplification region. Beta particles pass through the glass window into the drift region, ionizing the background gas. (In contrast with conventional Geiger counters, this gas is at atmospheric pressure.) The electrons are slowly accelerated into the amplification region. In the amplification region the electrons are quickly accelerated through a higher field region resulting in an electron cascade. Designing the drift region to be much larger than the amplification region allows pulses that are not a function of the entry position of the beta particle, but rather a function of beta particle energy.

The D-microGeiger is a double-stacked device with aligned cavities (Fig. 3). The glass substrate between the two cavities, which can have varying thickness, provides calibrated energy absorption. Lower energy beta particles are only detected in cavity 2, higher energy particles are detected in both cavities. The fabrication process uses two glass wafers and one Si wafer that is etched in EDP.
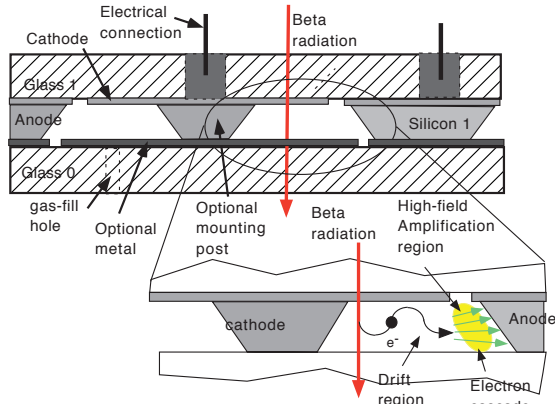

Fig. 2: The microGeiger device utilizes dissolved silicon bonded to glass as the anode-cathode configuration. Beta radiation passing through the drift region creates liberated electrons, which travel to the amplification region, creating an electron cascade.

Macro-scale gas-based devices have been widely used in the field of radiation detection [1]. Virtually all gas-based detectors rely on the impinging radiation ionizing the fill gas, with the resulting electrons, accelerated by an electric field, ionizing more neutral species, thereby creating an avalanche breakdown. The general form of the electron density in a cascade of length x is given by:

$$n(x) = n(0)\exp(\alpha x) \qquad (1)$$

Here, α is the first Townsend coefficient of the gas, a function of the gases ionizability, and electron capture cross section.
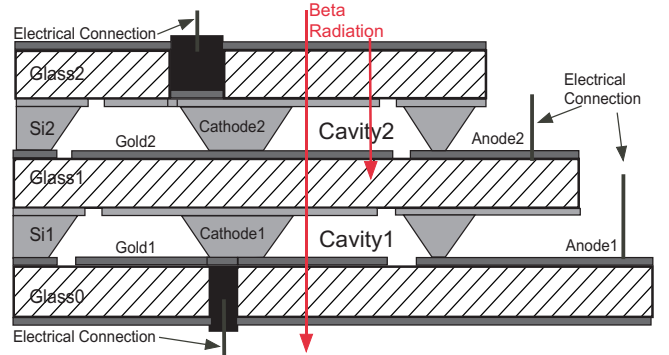

Fig. 3: D-microGeiger has two overlapping detection cavities as well as two separate electrical connections to the cathode. This feature provides a differential measurement allowing for energy spectroscopy.

Typical detectors fall into four regimes of operation defined by the applied electric field, electrode geometry, and the pressure and species of fill gas (Fig. 4). The four regimes all have electric discharges with differing physical properties. (These regimes apply to both beta particles and photons like X-rays and gamma particles). The regime with the lowest voltage is the ion saturation region, where the only charge collected is from gas directly ionized by impinging radiation.

As the voltage across the device is increased further, avalanche breakdown begins to occur, and the amount of collected current increases. This is the proportional region: the amount of current is roughly proportional to the energy of impinging X-rays or gamma particles, as photon radiation is completely absorbed by the background gas. In contrast, impinging beta particles impart only a portion of their kinetic energy to the ionization of gas, so the resulting current created is not correlated to the beta energy; the proportional region is more limited for beta particles.

As the voltage is increased, the dependence of the current pulse upon the energy of the radiation is diminished even for photon radiation. This is primarily due to the difference in mobilities between ions and electrons. In this limited proportionality regime, the much slower ions are sufficient in quantity to create a space-charge region which distorts the local electric fields. This limits the total charge, such as that created by avalanching, in a manner that is dependent on the electric fields. (Similar space-charge regions have been found to be the reason for lower charge densities in previously reported microplasmas [8].)

As the voltage is increased even further, the impinging radiation generates a self-sustaining discharge; this is the Geiger-Muller region.
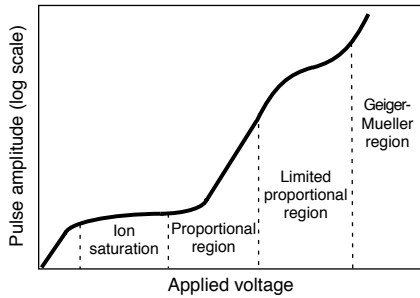
Fig. 4: Gas-based radiation detectors have four regimes of operation that are defined by the applied voltage.

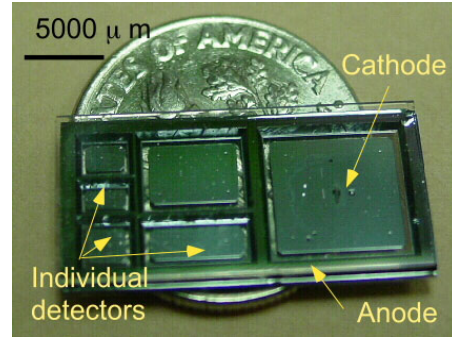

Fig. 5 (a-upper) The microGeiger die contains multiple detector cavities and is orders of magnitude smaller than traditional tubes. (b-lower) Backside of the microGeiger device.

III. DEVICE FABRICATION

Both microGeiger devices are fabricated in either a two or three mask process. The first mask defines a boron-diffused etch stop in a Si wafer. Mask two patterns an oxide which defines a region where silicon is etched. This silicon wafer is anodically bonded to a Pyrex™ wafer, which has been optionally inlaid with a thin film of metal to shape the electric filed within the cavities. The silicon is etched, forming structural offsets, and boron-doped anodes and cathodes. The stack is diced and bonded to a second glass wafer, providing the capability of gas packaging. Photographs of the final die with six independent cavities is shown in Fig. 5.

IV. EXPERIMENTAL RESULTS

Unsealed devices have been tested in a flow chamber to permit the comparison of various fill gases (Fig. 6). (Final devices will have the gas sealed within them, and will not require the chamber.) The background gas flows into the microGeiger device through input ports machined into the glass window. The gases which were evaluated include helium and neon. Helium was chosen for its lower ionization energy; this allows a larger current pulse at microscale dimensions. Neon also has a low ionization energy, but is potentially easier to package. In the test set-up DC power was provided to a capacitor which powered the anode; the cathode was grounded. Figure 7 shows a uranium ore sample, and calibrated ^{90}Sr, ^{60}Co and ^{204}Tl samples that were used to test the devices. Figure 8 illustrates the counting rate of one chamber in the microGeiger as a function of the distance from the detector. The normalized decline in counts is similar to that measured with a conventional detector, an Electro-Neutronics CDV-700.

Figure 9 shows the counts per minute as a function of the thickness of the glass windows. As the thickness of the window increases, more beta radiation is absorbed before it reaches the encapsulated gas. This illustrates that standard glass wafers from 500-750 μm can be utilized for fabrication – providing a varying range of absorbers for the D-microGeiger device.
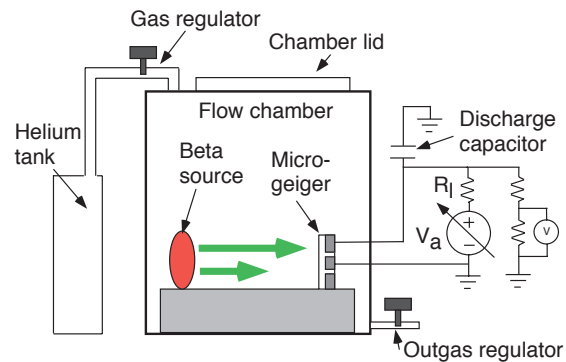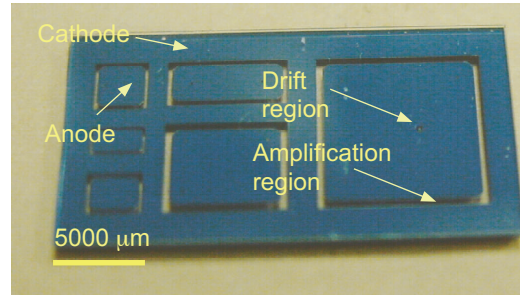

Fig. 6: Preliminary test setup for the microGeiger device in a tank that permits the gas within the cavities to be changed.

The microGeiger device was tested with a variety of radioactive isotopes, and fill gases. The corresponding results are shown in Fig. 10. Count rates were measured for three different cavity dimensions (8x8 mm, 4x4.5 mm, and 2x2 mm), and two isotopes, ^{90}Sr and ^{60}Co. The count rate can be seen to increase as the cavity size increases, providing more collection area, for all isotopes and fill gases. In the D-microGeiger, higher energy particles penetrate both cavities while lower energy particles do not (Fig. 3). Figure 11 shows different isotope signatures by the relative counts from the two cavities, demonstrating the first energy spectroscopy of beta particles and isotope discrimination in a Geiger counter. The current pulses from a ^{90}Sr source are shown in Fig.12. Beta particles typically have a range of energies ranging from zero to the endpoint energy, characteristic of the isotope [1], and this, along with statistical variations in breakdown charge produced is responsible for the variation in pulse heights.

Fig. 7: Naturally occurring uranium ore (left) and calibrated 0.1-1 μCurie isotope samples of various materials used to test devices.
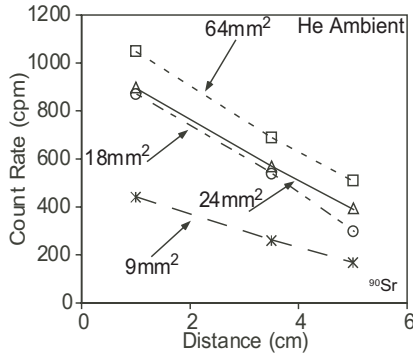

Fig. 8: Count rates decrease with increasing source distance as well as decrease with smaller cavity sizes. Four cavity sizes were tested at three separations from the sources.
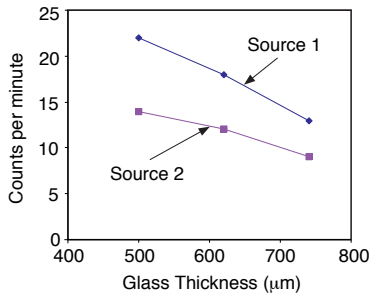

Fig. 9: The relative counts per minute from two different sources are diminished by a factor of about two as the thickness of the glass window increases from 500 μm to 750 μm.
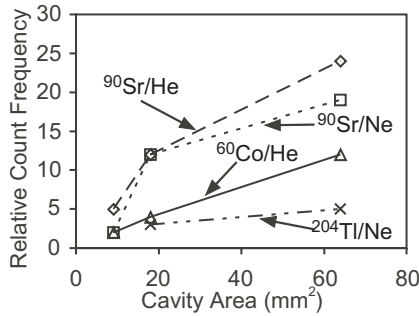

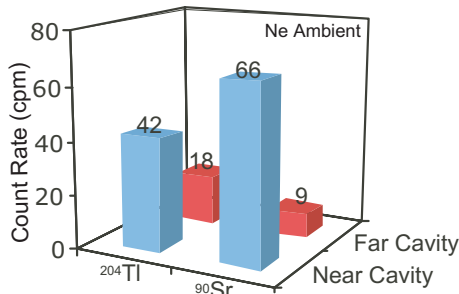Fig. 10: Relative counting rates for varying cavity sizes and varying gas environments.

Fig. 11: Count rates for the D-microGeiger detecting two different isotopes, including counting rates for the upper and lower cavities. The upper cavity consistently detected more particles than the lower cavity confirming the assumption that the higher energy beta particles are detected by both cavities while the lower energy particles are detected by the upper cavity alone.
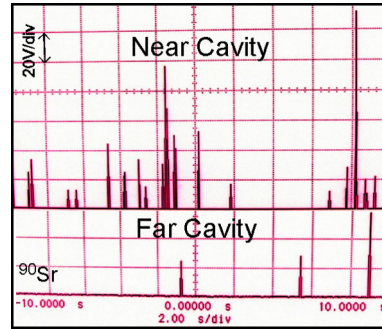

Fig.12: An oscilloscope trace of the upper (near) cavity of the D-microGeiger shows more pulses per unit time than the lower (far) cavity, for which the intermediate glass layer blocks the lower energy particles.

V. CONCLUSIONS

The microGeiger device was used to measure beta radiation produced from Uranium-238 ^{90}Sr, ^{60}Co, and ^{204}Tl, all beta-emitting isotopes. Counting rates of in excess of 1000 counts per minute were measured, and diminished as the source moved away in distance. Helium and neon were evaluated as background gases, as they provide a relatively low operating voltage. The D-microGeiger device, a dual-cavity detector used an inner glass layer to provide calibrated energy absorption was reported. Measurements demonstrate that beta particle energy spectroscopy can be performed in a miniaturized gas-based detector. With the additional information that is available, not only can the chemical nature of a radioactive isotope be determined, but also that the occurrence of false positives can be potentially reduced.

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