Radon Detection using a CMOS Alpha Sensor

by

Alexander John Heaslip Ross

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Department of Electronics

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Abstract

A radon monitor based on a 3 mm×3 mm alpha particle-detecting IC fabricated in a foundry CMOS process is reported. The alpha-detecting IC consists of a 16×16 array of *pn* junction diodes (sense diodes) that are precharged in reverse bias and then allowed to electrically float. Radon progeny are collected on the IC using an electrostatic concentrator. On-chip comparators detect the voltage change induced in a sense diode by an alpha particle emission from radon progeny passing through a sense diode. The comparator outputs are monitored by a microcontroller which processes the data and transmits it to a microcomputer using Bluetooth. The monitor has a sensitivity of 1.12 counts per hour per 100 Bq/m³ of radon activity. The monitor appears suitable for mass production at very low cost.

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List of Acronyms and Symbols

Acronyms

Acronym	Definition
AMS	Austria Micro Systems
BJT	Bipolar Junction Transistor
BPSG	Borophosphosilicate Glass
CMOS	Complementary Metal-Oxide-Semiconductor
DC	Direct Current
DRAM	Dynamic Random-Access Memory
EC	Electrostatic Concentrator
EPA	US Environmental Protection Agency
IC	Integrated Circuit
Logic High	Binary logic 1 or 3.3 V
Logic Low	Binary logic 0 or 0 V
MOS	Metal-Oxide-Semiconductor

MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
nMOS	n-type Metal-Oxide-Semiconductor
PC	Personal Computer
pMOS	p-type Metal-Oxide-Semiconductor
WHO	World Health Organization

Symbols

Symbol	Definition
C_{Bl}	Capacitance of sense and reference bit lines (215 fF).
$C_{bleeder}$	Capacitance of bleeder capacitor (21.3 fF).
C_{diode}	Capacitance of sense and reference diodes (645 fF).
ClockPrime	Clock generated from Sequence Controller to be used as the clock for the Row Controller.
I_{strike}	Current removed from a sense diode over a $1\mu s$ time interval. Used to model the reduction of charge in a sense diode after an alpha particle strike (160 nA).
S_{bleed}	Signal which connects reference diode to bleeder capacitor.
S_{ref}	Signal which connects reference diode to reference bit line.

$S_{refresh}$	Signal which refreshes diodes, capacitors, and bit lines on the IC.
S_{Wx}	Signal which connects sense diodes in row line x to their respective sense bit line.
V_{amp}	Differential amplifier's current mirror's bias voltage (2.50 V).
V_{bias}	Initial bias voltage used for sense and reference diodes and bit lines (1.25 V).
V_{Bl}	Initial voltage of a bit line ($V_{Bl} = V_{bias} = 1.25$ V).
V_{bleed}	Voltage reduced by the bleeder capacitor on reference diode (theoretically 40 mV).
$V_{bleeder}$	Voltage of the bleeder capacitor (initially 0 V).
V_{DIF}	Differential voltage seen by analog comparator.
V_{leak}	Voltage drop due to leakage in a floating sense or reference diode.
V_M	The negative input of the analog comparator. Connected to the reference bit line of the alpha particle-detecting CMOS IC.
V_P	The positive input of the analog comparator. Connected to the sense bit line of the alpha particle-detecting CMOS IC.
V_{ref}	Voltage of the reference diode.

V_{refBl}	Voltage of the reference bit line.
V_{sense}	Voltage of the sense diode.
$V_{senseBl}$	Voltage of the sense bit line.
V_{strike}	Voltage change in a sense diode due to an alpha particle strike (theoretically 250 mV).
V_{switch}	The input voltage where the analog comparator's output voltage is 50% of logic High voltage.

Chapter 1

Introduction

1.1 Motivation

Radon is a well-known human carcinogen and is the largest natural contributor of background ionizing radiation dose for the average person. As a result, it is estimated that upwards of 21,000 Americans and 1,400 Canadians die every year due to radon induced lung cancer [1]. Organizations such as the World Health Organization (WHO) have been taking a keen interest in raising awareness and advising countries on radon prevention and mitigation. The WHO recommends that action should be taken to reduce radon levels in buildings with more than 100 Bq/m³ [1]. However, individual countries can set their own threshold for corrective measures. Health Canada and the US Environmental Protection Agency (EPA) recommend that home owners should take action to reduce radon levels higher than 200 Bq/m³ and 148 Bq/m³ respectively [2, 3]. WHO, Health Canada, and the EPA all note that even low concentrations of radon still pose some risk for developing lung cancer [1–3]. As a result, there is a need for an inexpensive radon monitor that could be widely adopted.

1.2 Thesis Contributions

There is a variety of commercial radon detectors on the market. The most readily available detectors are typically one-time use, measuring a long-term average of the radon concentration. This property often makes these detectors unattractive from the viewpoint of many users. Other more sophisticated radon detectors are simply too expensive for the typical consumer.

At Carleton University, there has been a significant amount of research in developing a sophisticated, yet low-cost, radon monitor with high-volume production capabilities. In 2008, R.H. Griffin reported a simple yet sensitive radon monitor using a custom alpha particle-detecting MOS integrated circuit [4, 5]. This alpha particle-detecting IC was fabricated in a custom nMOS process in a university laboratory making it impractical to base a commercial monitor on such a chip.

This thesis is a continuation of the work done by Griffin. I have designed and fabricated an alpha particle-detecting IC in a foundry CMOS process. I have made substantial changes to the radon monitor to interface with the alpha particle-detecting CMOS IC and transmit data using Bluetooth. I have successfully detected radon gas using the radon monitor. It was determined that the radon monitor has a sensitivity of 1.12 counts per hour per 100 Bq/m³ of radon activity. My research was published in IEEE's 2016 Sensor Applications Symposium [6]. The monitor appears amenable to mass production at very low cost, and is therefore attractive for consumer applications.

1.3 Outline

Chapter 2 provides background on radon and identifies why it is a problem. A brief overview on current methods for radon detection will be presented. A discussion of background radiation and its effect on radon detection is also given. This chapter will also summarize previous work on detecting radon using an alpha particle-detecting nMOS integrated circuit.

Chapter 3 presents the analysis, design, and layout of the alpha particle-detecting CMOS integrated circuit.

Chapter 4 describes the methods used for testing the alpha particle-detecting CMOS integrated circuit. A discussion will follow on how the alpha particle-detecting integrated circuit was used to construct a complete radon monitor which was then successfully tested.

Chapter 5 will present the conclusions of this thesis as well as identify areas for future work.

Chapter 2

Background

2.1 Radon

Radon is a clear, colourless, odorless, tasteless, radioactive noble gas. Radon-222 is produced in the uranium-238 decay series, and is the most stable radon isotope with a half-life of 3.8 days [7]. Naturally occurring uranium-238 is commonly found in the earth's crust [3]. Once radon-222 is formed, it easily diffuses through the ground and into buildings, where it can accumulate [3]. Radon-222 decays with a 5.48 MeV alpha particle emission to polonium-218, which is often charged. This is the beginning of the sequence of short-lived radon progeny shown in Figure 2.1 [7].

The alpha particles emitted during radon or progeny decay can be very damaging to living tissue. If inhaled, radon and radon progeny pose a significant risk to lung tissue, and long-term exposure may lead to lung cancer [1,4]. The higher the radon exposure, the higher the probability of an individual developing lung cancer. This is especially prevalent for individuals who smoke, where their likelihood of developing lung cancer is significantly increased as shown in Figure 2.2 [3]. It is estimated that radon induced cancer contributes to 21,000 deaths or 3.7% of all cancer related deaths in the US as shown in Figure 2.3 [8].

Organizations such as the World Health Organization (WHO) have been taking

Figure 2.1: Decay chain of short-lived radon-222 progeny (Information from [7]).

a keen interest in raising awareness and advising countries on radon prevention and mitigation. The WHO recommends that action should be taken to reduce radon levels in buildings with more than 100 Bq/m³. However individual countries can set their own threshold for corrective measures. For example, the EPA's threshold for the United States is 148 Bq/m³ while Health Canada's threshold is 200 Bq/m³ [2, 3]. However, all acknowledge that even lower concentrations of radon still pose some risk for developing lung cancer [1]. As a result, there is a need for an inexpensive radon monitor that could be widely adopted in homes.

Recently, Health Canada has conducted a two-year cross-Canada study with 13,976 participants [9]. The participants were given a track-etch detector to place in their home's lowest floor for 90 days [9]. Track-etch detectors are one-time use, measuring a long-term average of the radon concentration [1, 9]. The study results revealed that 6.9% of all participants had radon levels higher than 200 Bq/m³ [9]. Some provinces such as Manitoba, New Brunswick and Yukon had more than 18% of

Figure 2.2: The increased risk for smokers with radon exposure in the US (Data from [3]).

Figure 2.3: The number of US radon induced lung cancer deaths in comparison to other types of cancers in 2010 (Data from [8]).

all homes above the recommended level. The City of Ottawa Health region and Region de l'Outaouais (Gatineau) have 6.2% and 12.9% respectively, above 200 Bq/m³ of radon concentration [9].

2.2 Radon Detection

There is a variety of commercial radon detectors on the market. Almost all detect radon indirectly by sensing the alpha particles emitted in the decay of radon or its progeny. One of the most common and inexpensive detectors is the track-etch detector, which relies on alpha particles leaving damage tracks in a polycarbonate substrate. After one month to a year the detector is returned to a specialized laboratory for track counting. Track-etch detectors are one-time use, measuring a long-term average of the radon concentration [1]. This property, combined with the need to return them for analysis, make these detectors cumbersome and unattractive from the viewpoint of many users.

Continuous radon monitors provide multiple benefits compared to their long-term averaging-only counterparts. Continuous radon monitors allow for short- and long-term measurements, usually directly displaying results to the user, removing the need to send them away for analysis. There are many different types of continuous radon monitors available, using ionization chambers, scintillators, semiconductors, or other detectors [1]. The following is an overview of a few common types of detectors.

Ionization chambers are used to detect ions that are generated by a charged particle traveling through gas. An ionization chamber typically contains electrodes in an enclosed gas. The electrodes provide an electric field which will move the electron and ion pair towards the negative and positive electrode respectively. This generated current is measured externally [10]. Often for radon detection, air is used as the gas surrounding the electrodes. This air is allowed to diffuse in and out of the chamber

Figure 2.4: Radon detection using ionization chamber.

freely as shown in Figure 2.4. If radon or radon progeny in the air decays with an alpha particle emission, it will ionize the air, generating current [11]. This system can also be equipped with a fan for continuous air flow or sampling [11].

Scintillators are used to convert the kinetic energy of a charged particle into light. Scintillators are often used with photomultiplier tubes or photodiodes to convert the generated light into an electrical signal. The scintillating material can be organic or inorganic, where organic materials have a lower efficiency but faster response times [10]. A recent radon detector using a scintillator can be seen in [12], where an inorganic $\text{ZnS}(\text{Ag})$ scintillator on top of a 4×4 array of 3 mm diameter silicon photomultipliers was used. An external readout circuit is used to amplify current produced by the photomultipliers. A ventilation system containing a fan was used to provide continuous flow of air across the scintillating material [12].

Semiconductors can be used to detect the electron-hole pairs generated along the path of a charged particle in the semiconductor itself. There are many different types of semiconductor detectors using a variety of different materials [10]. Recently bipolar junction transistors (BJT) on high-resistivity (111) silicon substrates have been used to detect alpha particles. These devices utilize the internal signal amplification of BJTs which significantly simplifies readout circuitry as shown in Figure 2.5 [13]. For radon detection, radon progeny was collected on the surface of the BJT IC using an

Figure 2.5: Readout circuitry used in BJT based radon detector.

electrostatic concentrator [13].

The semiconductor detectors discussed above all require specialized processing and manufacturing. Silicon diodes however, are ideal for alpha particle detection [10] and can be created in a standard low-cost CMOS foundry process. In addition, readout circuitry can be monolithically integrated along side the silicon diodes. This allows for an alpha particle sensor to be fabricated at a reduced cost and allows for mass production. A method of monitoring radon gas by detecting the alpha particles emitted during progeny decay using a diode array will be presented here.

2.3 Detecting Alpha Particles Using Silicon Diodes

One method to detect alpha particles using a silicon pn diode is to reverse bias the device and then leave it electrically floating. If an alpha particle strikes the diode, it will ionize the silicon creating a plasma of electron-hole pairs along a track. If the track intersects the pn junction depletion region, the depletion region field will be deformed to follow the plasma, creating a “charge funnel” that sweeps excess charge carriers across the depletion region. Electrons will be swept to the n -type side and

the holes to the p -type side. As a result, the voltage across the floating reverse biased junction will be diminished [14].

Radon's progeny, polonium-218, emits an alpha particle with an energy of 6.00 MeV [7]. The average ionization energy for an electron-hole pair in silicon is 3.6 eV. Thus polonium-218 can generate approximately 1.7 million electron-hole pairs [14]. However not all electron-hole pairs are collected. Fortunately, the collection of electron-hole pairs is enhanced by the alpha particle distorting the pn diode's electric field in the depletion region. The distorted electric field will extend along the alpha particle path, far into the bulk silicon as shown in Figure 2.6. This electric field will then funnel charge generated in the bulk silicon into the diode. As a result, it is reasonable to assume that approximately 1 million electron-hole pairs will be collected, however there will be variation on the number of collected pairs [14]. The change in voltage resulting from an alpha particle strike can be approximated by:

$$\Delta V = \frac{Q}{C} \quad (2.1)$$

where Q is the collected charge after an alpha particle strike and C is the capacitance of the diode. The total capacitance of the diode is the sum of the bottom and side wall capacitances, giving the total capacitance:

$$C = \frac{C_{j0b}}{[1 - \frac{V_D}{V_{bi}}]^m} \times A + \frac{C_{j0s}}{[1 - \frac{V_D}{V_{bi}}]^m} \times P \quad (2.2)$$

C_{j0b} and C_{j0s} are the per unit area and per unit length capacitances of the bottom and side wall of the diode. A is the surface area of diode and P is the perimeter of the diode. V_{bi} is the built-in potential, m is the grading coefficient and V_D is the reverse bias voltage [15].

If a $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ pn diode from Austria Micro Systems $0.35\text{ }\mu\text{m}$ CMOS process with a reverse bias of 1.25 V is used, the above theory predicts a voltage drop of

Figure 2.6: An illustration of an alpha particle distorting the electric field of a silicon diode. In (a) a diode is reverse biased and left to electrically float. When an alpha particle strikes the diode in (b), the diode's electric field in the depletion region is distorted, funneling charge from the silicon bulk into the diode. This effect enhances charge collection and helps diminish the voltage across the floating reverse biased junction in (c).

250 mV will occur in response to an alpha particle strike. This significant voltage change may be easily detected using simple readout circuitry.

2.4 Background Radiation

For accurate measurements of radon gas concentrations, it is important that the IC using diodes for detecting radon progeny alpha particles be insensitive to background radiation. The terrestrial radiation environment is dominated by alpha particle radiation and secondary radiation products produced by high and low-energy cosmic rays [16]. One source of alpha particle radiation comes from uranium-238 and thorium-232 impurities in IC packaging. Another source of alpha particle radiation occurs in lead solder where the radioactive lead-210 eventually decays into polonium-210, and polonium-210 decays with an alpha particle emission. These impurities were the dominant cause of soft errors in DRAMs in the 1970s, with rates as high as 100 counts/cm² h. Currently, error rates due to packaging are below 0.001 counts/cm² h [16]. With an IC area less than 1 cm², the amount of background

radiation due to packaging impurities is insignificant.

Cosmic rays create a large array of secondary particles when they interact with the atmosphere. The most significant high-energy cosmic ray particles created are neutrons, since they have highest flux at terrestrial levels. Neutrons interact with silicon elastically and inelastically, resulting in a burst of light charged particles such as protons and alpha particles [16]. Low-energy cosmic ray neutrons (< 1 MeV neutron energy) can interact with boron-10, which is unstable when exposed to neutrons. Boron-10 is often found in p-type doping and borophosphosilicate glass (BPSG). When boron-10 interacts with the neutron, it produces a lithium-7 nucleus and an alpha particle [16]. While the flux of both high and low-energy neutrons are significant at high elevations, at typical household elevations the flux is only 43.6 neutrons/cm² h (Yorktown Heights with altitude of 167 m) [17,18]. It would be expected that on average 3.9 neutrons would strike a 0.3 cm×0.3 cm IC every hour. In addition, the mean free path of neutrons is about 10 cm meaning that it will likely pass through a typical 500 μ m IC completely undetected [10]. Therefore due to the amount of background radiation at terrestrial levels and the low probability that they would interact with a thin silicon die, the amount of cosmic rays detected by an IC is insignificant.

2.5 Alpha Particle-Detecting MOS Integrated Circuit

A solution for radon detection using silicon diodes was developed at Carleton University by R.H. Griffin and discussed in [4,5,19–23]. This monitor used an IC containing an array of *pn* diodes to detect alpha particle radiation from radon progeny. The diodes were structured in a folded bit line structure similar to a DRAM. As a result the sensor is referred to as an “ α RAM”. One benefit to this approach was that if one

diode in the array became defective, it could be ignored in readout. In contrast, a single defect would render a large-area single diode detector unusable.

A conventional nMOS cross-coupled latched sense amplifier was used to detect voltage changes in the diodes due to an alpha particle strike. This was accomplished by connecting a diode and reference voltage to the sense amplifier through bit lines. If the diode's voltage was less than the reference voltage, an alpha particle was detected. The sense amplifiers and additional digital control circuitry were monolithically integrated with the α RAM.

Radon was measured indirectly by detecting alpha emissions from radon or its progeny. However since alpha particles travel at most a few centimeters in air, radon or its progeny must be brought close to the alpha-detecting IC [5]. Electrostatics was used to concentrate charged radon progeny, polonium-218, onto the surface of the IC [24]. The electrostatic concentrator (EC) was built from a polyethylene funnel where the inside was metalized using 32 μ m thick copper tape [22]. The copper tape was separated into two sections to create a stronger sweep field inside the cone. The top of the cone was covered by copper mesh which was attached to the top electrode as shown in Figure 2.7. The electrostatic concentrator used has a 243 mL capacity with a top and bottom diameter of 21 mm and 104 mm respectively [22]. Since the bottom diameter of the electrostatic concentrator was significantly larger than the IC, it will produce a homogeneous radon progeny distribution across the entire IC. This makes the radon monitor less sensitive, since not all the radon progeny is concentrated onto the IC. A potential of 1000 V and 800 V was applied to the top and bottom electrode respectively [22]. To create this high voltage, a 50 stage Cockcroft-Walton charge pump from [22] shown in Figure 2.8, was used to convert a 15 V peak-to-peak square wave from a LM555 timer into the DC voltages.

The simplified radon monitor from [4] is illustrated in Figure 2.9, where the bottom of the electrostatic concentrator funnel is positioned on top of the alpha

Figure 2.7: Cross-section of the electrostatic concentrator.

Figure 2.8: Simplified high voltage generating circuit.

particle-detecting MOS IC. A LabJack U12 DAQ connected to a computer running Agilent VEE Pro 6.0 was used for the data acquisition and display of the alpha particle sensor's signals [5]. Other radon monitors from Carleton University have implemented data acquisition using a microcontroller with an integrated wireless transceiver (EZ430-RF2500) [21].

The radon monitor successfully detected radon with a sensitivity of 2.2 counts per hour per 100 Bq/m³ of radon activity. It should be noted that only the alpha particles emitted towards the IC are detected. However a significant limitation of this monitor is that its alpha particle sensor was fabricated in a custom nMOS process in Carleton University's MicroFabrication Facility [5]. Clearly it would be impractical to base a commercial monitor on such a chip. As a result this IC was redesigned

Figure 2.9: An illustration of the radon monitor from [4] with the alpha particle-detecting MOS IC.

and fabricated in a foundry CMOS process. The radon monitor was also changed to interface with the alpha particle-detecting CMOS IC.

Chapter 3

Alpha Particle-Detecting CMOS IC Design

3.1 Overview of the Alpha Particle-Detecting CMOS IC

The CMOS alpha particle-detecting IC was designed following an approach similar to that used for the MOS IC in [4, 5, 19–23]. The alpha particle sensitive silicon diodes, or sense diodes, are structured in a 16×16 array as shown in Figure 3.1. This structure, like in [4, 5, 19–23], is similar to the folded bit line architecture often used in DRAM [15]. To measure their voltage, the sense diodes are connected via transmission gates to their respective bit lines. Analog comparators at the ends of the bit lines are used to compare the sense diode’s voltage to a reference voltage. The analog comparator will output a digital signal indicating whether or not the sense diode has detected an alpha particle. The entire sensor is managed by digital control blocks which are used to connect and recharge the sense diodes, as well as creating a reference voltage and handshaking signals. The alpha particle-detecting CMOS IC was designed and fabricated using Austria Micro Systems 0.35 μm CMOS process (<http://ams.com/eng>) which is compatible with the TSMC 0.35 μm CMOS process

Figure 3.2: Sense diode illustration showing the double guard ring with a thickness of D and the square pn junction with a square edge length of S .

depends on the generated charge and the capacitance of the diode. Additionally, the sense diode's pn junction size and reverse bias will influence the change of junction potential after an alpha particle strike.

The Austria Micro Systems (AMS) $0.35\ \mu\text{m}$ CMOS process has multiple types of diodes. For maximum voltage change, minimum diode capacitance is required as given by Equation 2.1. AMS's pn diode consisting of an n -well in a p -substrate was used since it has the lowest zero-bias capacitance per unit area.

As the reverse bias of the pn junction increases, the width of the depletion region increases following [25]:

$$W_D = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) (V_{bi} - V_D)} \quad (3.1)$$

where ϵ_s is the permittivity of silicon, N_A and N_D are the acceptor and donor concentrations, and q is the charge of an electron. The capacitance per unit area of the pn junction is [25]:

$$\bar{C}_D = \frac{\epsilon_s}{W_D} \quad (3.2)$$

This results in an increased voltage drop due to an alpha particle strike with an

Figure 3.3: Voltage change in a $100\ \mu\text{m} \times 100\ \mu\text{m}$ sense diode due to an alpha particle strike as a function of reverse bias (assuming the collection efficiency predicted by [14] remains constant).

increased reverse bias, as per Equation 2.1 and shown in Figure 3.3. A large voltage drop is desirable for ease of detection by a comparator, and Equation 2.2 shows that a large reverse bias is required for a large voltage drop after an alpha particle strike. However, the biasing requirements of the analog comparator limits the maximum sense diode voltage. A reverse bias of 1.25 V was generated externally using a bandgap voltage regulator. Alternatively, a low-noise bandgap reference could have been monolithically integrated on-chip to provide the reverse bias.

The area of the pn junction significantly affects the voltage change due to an alpha particle strike. The voltage drop versus square edge length of the pn junction is shown in Figure 3.4, assuming the collection efficiency predicted by [14]. As square edge length (or similarly area) decreases, the voltage drop due to an alpha strike increases. However the width, D , of the double guard ring remains constant regardless of pn junction's size. Therefore a smaller pn junction uses less of the total sense diode

Figure 3.4: Voltage change in a sense diode due to an alpha particle strike, with a 1.25 V reserve bias, as a function of size (assuming the collection efficiency predicted by [14] remains constant).

area as shown in Figure 3.5. Therefore less area is required for a sense diode with a large pn junction than multiple smaller sense diodes with an equivalent combined pn junction area. In addition, a larger pn junction results in less sensitivity to lower energy background radiation, since the voltage drop in the sense diode is less.

A sense diode containing a $100\ \mu\text{m} \times 100\ \mu\text{m}$ pn junction with a 1.25 V reserve bias (V_{bias}) was used, which achieves a 248 mV voltage drop after an alpha particle strike (assuming the collection efficiency predicted by [14]).

To verify the circuit design of the alpha particle-detecting IC, the response of the sense diode to an alpha particle strike must be modeled for use within a circuit simulator. The most simple model uses an ideal piecewise linear current source in parallel with the sense diode as shown in Figure 3.6. The ideal piecewise linear current source will remove charge from the sense diode equivalent to the collected charge after an particle strike. The required current to remove the equivalent charge

Figure 3.5: Percentage of sense diode area occupied by a *pn* junction.

from the sense diode is:

$$I_{strike} = \frac{dQ}{dt} = \frac{\Delta Q}{\Delta t} \quad (3.3)$$

From [14] approximately 1 million electron-hole pairs will be collected, or a difference in charge of $\Delta Q = 1.60 \times 10^{-13} \text{ C}$. If this charge is removed in $\Delta t = 1 \text{ } \mu\text{s}$, then the amplitude of the current pulse from the ideal piecewise linear current source is $I_{strike} = 160 \text{ nA}$. This simple model was simulated using Cadence Virtuoso resulting in a 240 mV voltage drop.

Figure 3.6: A simple model to simulate an alpha particle strike in a circuit simulator.

Figure 3.7: Results of the simple model to simulate an alpha particle strike on a $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ diode, simulated using Cadence Virtuoso.

3.3 Sense and Reference Bit Lines

An analog comparator is used to detect a voltage drop due to an alpha particle strike. As shown in Figures 3.8 and 3.1, the positive and negative inputs of the analog comparator are connected to a sense diode and reference voltage respectively. To conserve area, multiple sense diodes are connected by transmission gates to the same analog comparator using a bit line which is also referred to as sense bit line. Using digital control blocks, only one sense diode will be connected to the analog comparator at a time.

For biasing the analog comparator the bit lines are initially charged to the same potential (V_{bias}) as the sense diode. However after an alpha particle strike, charge sharing will occur when a sense diode and a bit line are connected together. The final

Figure 3.8: An analog comparator connected to the sense diode and a reference voltage. This reference voltage is created using a reference diode and a bleeder capacitor to remove charge from the reference diode.

voltage of both the sense diode and sense bit line when connected together is:

$$V_{senseBl} = \frac{C_{Bl}V_{Bl} + C_{diode}V_{sense}}{C_{Bl} + C_{diode}} \quad (3.4)$$

where C_{Bl} and V_{Bl} are the capacitance and initial voltage of the sense bit line, C_{diode} and V_{sense} are the capacitance and the voltage of the sense diode, and $V_{senseBl}$ is the final voltage of the sense bit line and sense diode.

From Equation 3.4, charge sharing reduces the effective voltage drop seen at the comparator's input due to an alpha particle. Fortunately the capacitance C_{diode} of a $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ pn sense diode is considerably larger than the capacitance C_{Bl} of the sense bit line, for short bit lines. However when more sense diodes are on the same bit line, the length of the bit line is increased, increasing the capacitance C_{Bl} of the bit line. This results in a smaller voltage drop seen by the comparator due to an alpha particle as shown in Figure 3.9. Due to area constraints only 16 sense diodes per sense bit line were used. However more sense diodes could have been attached on the same bit line with a large effective voltage drop remaining.

The reference voltage is generated using a reference diode, identical to the sense diode in size. The reference voltage needs to be slightly less than the sense diode's initial voltage V_{bias} to differentiate between any voltage drop due to leakage and an alpha particle strike. As a result, the reference diode is charged to the same potential V_{bias} and then reduced by V_{bleed} . Like the sense diode, when the reference diode is connected to the bit line, charge sharing occurs where the final voltage of both the reference diode and reference bit line is:

$$V_{refBl} = \frac{C_{Bl}V_{Bl} + C_{diode}V_{ref}}{C_{Bl} + C_{diode}} \quad (3.5)$$

where V_{ref} is the voltage of the reference diode before being connected (which will be less than V_{bias}), and V_{refBl} is the final voltage of the reference bit line and reference

Figure 3.9: The remaining or effective voltage drop due to an alpha particle strike after charge sharing between sense diode and sense bit line.

diode.

If the two bit lines are identical, the differential voltage seen by the analog comparator is:

$$V_{DIF} = V_{refBl} - V_{senseBl} = \frac{C_{diode}}{C_{Bl} + C_{diode}} (V_{ref} - V_{sense}) \quad (3.6)$$

Equation 3.6 shows that there is no dependence on bit line voltage V_{Bl} if both bit lines are initially charged to the same potential. Also to maximize the differential voltage across the comparator, C_{Bl} must be minimized (reduce the number of sense diodes on a bit line). If the sense diode's voltage is reduced by V_{strike} after an alpha particle strike and reference diode's voltage is reduced by V_{bleed} , Equation 3.6 becomes:

$$V_{DIF} = \frac{C_{diode}}{C_{Bl} + C_{diode}} (V_{strike} - V_{bleed}) \quad (3.7)$$

If an alpha particle strike occurs, then $V_{strike} > V_{bleed}$ and $V_{DIF} > 0$ so long as V_{bleed} is small.

Equations 3.6 and 3.7 both assume that the bit lines and diodes are well matched and the same leakage (V_{leak}) exists in both reference and sense diodes. For the last condition to be true, it would require one reference diode for each sense diode, which would use a significant amount of area. Therefore only one reference diode is used per reference bit line and will be refreshed whenever a sense diode is compared. As a result, the sense diodes will have a larger voltage drop than the reference diode due to leakage due to a larger elapsed time since the last refresh. The differential voltage seen by analog comparator becomes:

$$V_{DIF} = \frac{C_{diode}}{C_{Bl} + C_{diode}}(V_{strike} + \eta V_{leak} - V_{bleed}) \quad (3.8)$$

where η is the leakage difference between the reference diode and the sense diode. This mismatch in leakage is compensated by ensuring that the V_{leak} is insignificant by removing $V_{bleed} \gg V_{leak}$ from the reference diode. In addition, V_{leak} can be further reduced by reducing the floating time between voltage refreshes.

To remove V_{bleed} from the reference voltage V_{ref} , the reference diode is charged to the same potential V_{bias} as the sense diodes and left to electrically float. While floating, the reference diode is connected to the poly bleeder capacitor from Figure 3.8 which removes charge via charge sharing. This will slightly decrease the reference diode's potential to:

$$V_{ref} = \frac{C_{diode}V_{bias} + C_{bleeder}V_{bleeder}}{C_{diode} + C_{bleeder}} = V_{bias} - V_{bleed} \quad (3.9)$$

where $V_{bleeder}$ is the voltage of the bleeder capacitor generated externally to the IC, $C_{bleeder}$ is the capacitance of the bleeder capacitor, and C_{diode} is the capacitance of the reference diode which is the same as the sense diode. Using a small bleeder capacitor

Figure 3.10: Differential voltage seen by analog comparator versus voltage V_{bleed} removed from reference diode.

of $C_{bleeder} = 21.3$ fF and a bleeder voltage of $V_{bleeder} = 0$ V, a voltage $V_{bleed} = 40$ mV is removed resulting in a differential voltage across the comparator of -30 mV when no alpha particle strike has occurred as shown in Figure 3.10. When an alpha particle strike occurs, a differential voltage of 156 mV will be seen by the comparator as shown in Figure 3.10.

Cadence Virtuoso was used to verify this analysis and the accuracy of Equation 3.7. Figure 3.11 shows the sense diode and reference voltage generating circuit from Figure 3.8, where the transmission gates have been replaced by ideal switches. The bit line capacitance $C_{Bl} = 215$ fF has also been included for simulation. First S_{bleed} is asserted, connecting the reference diode with a voltage $V_{ref} = 1.25$ V to the bleeder capacitor with a voltage $V_{bleeder} = 0$ V. Charge sharing between the reference diode and capacitor results in $V_{bleeder} = V_{ref} = 1.21$ V which is $V_{bleed} = 40$ mV less than V_{bias} , as expected from equation 3.9. I_{strike} then removes charge from the sense

Figure 3.11: Sense diode and reference voltage generating circuit connected via ideal switches to their respective bit lines.

diode to simulate an alpha particle strike, resulting in the voltage across the sense diode of $V_{sense} = 1.01$ V. Both S_{ref} and S_{Wx} signals are asserted, connecting the sense and reference diodes to their respective bit lines. Charge sharing with the bit lines results in the sense diode increasing to $V_{sense} = V_{senseBl} = 1.07$ V and the reference diode increasing to $V_{ref} = V_{refBl} = 1.22$ V. Therefore the voltage seen by the comparator is $V_{DIF} = 153$ mV as shown in Figure 3.12. This result is very close to the theoretical 156 mV calculated by Equation 3.7, shown in Figure 3.10.

In Figure 3.13 the ideal switches are replaced with transmission gates and the previous simulation were repeated as shown in Figure 3.14. The simulated voltage seen by the comparator is now $V_{DIF} = 143$ mV which is less than with the ideal switches. This difference is due to the gate source capacitance C_{gs} of the transmission

Figure 3.12: Simulation results of sense diode and reference voltage generating circuit connected via ideal switches to their respective bit lines.

gates, which was ignored in the analysis. The transmission gates each have an nMOS and a pMOS with their drains and sources connected in parallel. As a result, the transmission gates have two parallel gate source capacitances on each well. With two transmission gates connected to a single node, there is a total of $C_{gs,\text{total}} = 4 \times C_{gs} \approx 4 \times 1 \text{ fF} = 4 \text{ fF}$ extra capacitance added.

In the analysis it was assumed that the switching component did not contribute to the capacitance of the sense diode. This is still approximately true since sense diode $C_{\text{diode}} = 645 \text{ fF} \gg C_{gs,\text{total}}$. However the bleeder capacitance $C_{\text{bleeder}} = 21.3 \text{ fF}$ is not significantly greater than $C_{gs,\text{total}}$, and the transmission gate's gate source capacitance will increase the total capacitance on the V_{bleeder} node considerably. Therefore, the total capacitance on the V_{bleeder} node is increased to about 25.3 fF, and from equation 3.9 the expected V_{ref} is now 1.20 V, which agrees with simulation.

Figure 3.13: Sense diode and reference voltage generating circuit connected via transmission gates to their respective bit lines.

Sense and Reference Bit Line Simulations with Transmission Gates

Figure 3.14: Simulation results of sense diode and reference voltage generating circuit connected via transmission gates to their respective bit lines.

A small section of layout of the sense and reference bit lines is presented in Figure 3.15. This layout shows the bit lines extending between two columns consisting of sense and reference diodes. Due to the bleeder capacitors' small size, they are conveniently placed between the two bit lines. Both the reference and sense bit lines are made to be the same length and width for matching. Since the sense bit line will have 16 transmission gates, 16 transmission gates are also connected to the reference bit line for symmetry. These transmission gates (referred to as false transmission gates in Figure 3.15) are hard connected in an off state. In addition to always being off, the end not connected to the reference bit line is connected to the same initial potential of a sense diode V_{bias} .

Figure 3.15: Sense and reference diode and bit line layout.

3.4 Analog Comparator

The analog comparator in Figure 3.16 uses a typical pMOS differential amplifier input to detect a voltage drop, with a push-pull amplifier output to provide rail-to-rail output voltage. The layout of the analog comparators at the end of their respective bit lines can be seen in Figure 3.17. The differential amplifier's current mirror is biased using $V_{amp} = 2.5$ V which is generated off chip. Using an external bias voltage was a poor choice as V_{amp} would not be able to follow temperature, supply voltage, and process variations. However, being able to tune the amplifier's bias voltage was a desired feature in the initial design to augment testing capabilities.

The analog comparator is to switch fully from logic High to Low when there is an alpha particle strike. As a result, the switching point (input offset) and switching width (or voltage gain) of the comparator are important. The switching width will be defined as the change in input voltage difference between 10% and 90% of logic High voltage at the output. Designing a comparator to have a high voltage gain will provide a small switching width. The switching point will be defined as the input voltage where the output is 50% of logic High voltage. For an ideal comparator the switching point for this IC would occur at $V_{switch} = V_{bias} = 1.25$ V with a switching width of 0 V (which would require zero input offset and infinite voltage gain). Using Cadence Virtuoso, a DC simulation of the analog comparator with MOSFET model corners at different temperatures can be seen in Figure 3.18. The positive input of the comparator representing the voltage on the sense bit line was swept and the negative input was held constant at $V_M = V_{bias} = 1.25$ V (identical to the reference bit line voltage V_{refBl}). From this simulation the worst-case occurs with the fast-fast MOSFET model corner at low temperatures, where the switching point occurs at 1.248 V. Therefore the magnitude of the input differential offset is taken to be 2 mV. Since the magnitude of the differential offset is significantly smaller than the

Figure 3.16: Schematic of analog comparator.

magnitude of V_{DIF} with and without an alpha particle strike (30 mV and 156 mV respectively), this offset is tolerable. A switching width of about 2 mV is also seen in Figure 3.18 meaning the analog comparator can theoretically resolve differential voltage differences greater than 2 mV.

Figure 3.17: Layout of analog comparator.

Figure 3.18: DC simulation of analog comparator.

3.5 Digital Control Blocks

The sense diode array and reference voltage generator is controlled by two digital control blocks: the row and sequence controllers. The row controller continuously cycles through all 16 rows, sequentially connecting rows of sense diodes to their respective sense bit lines using transmission gates. The sequence controller then operates on the selected row by cycling through the following tasks:

1. The reference and sense diodes are connected, via transmission gates, to their respective bit lines which are connected to an analog comparator as shown in Figure 3.19a. The analog comparator compares the two bit lines and determines whether or not an alpha particle has struck the sense diode. At the same time, the sequence controller pulses a handshaking signal. This signal informs an off-chip microcontroller that the information on all 16 comparators' output data is valid.
2. The bit lines are connected together and the reference and sense diodes are recharged through the bit lines to their initial voltage. Simultaneously, the bleeder capacitor's potential is refreshed back to $V_{bleeder}$ as shown in Figure 3.19b.
3. The two bit lines are then separated and reference and sense pixel are disconnected. The bleeder capacitor is also disconnected from $V_{bleeder}$ as shown in Figure 3.19c.
4. The bleeder capacitor and reference diode are then connected together as shown in Figure 3.19d. This allows some charge to transfer from the reference diode to the bleeder capacitor (charge sharing). This results in a small voltage drop in the reference diode, providing the reference voltage for the analog comparator.

5. The reference diode is then disconnected from the bleeder capacitor shown in Figure 3.19c. The sequence controller pulses the ClockPrime signal, shown in Figure 3.20, which causes the row controller to shift to the next row of sense pixels. The sequence controller's cycle is then repeated.

Figure 3.19: Illustration of the tasks performed by the sequence controller.

The sequence and row controller, as shown in Figure 3.20, use a shift register and logic to generate the control signals, row signals and ClockPrime signal. The shift registers of the sequence controller is clocked by an external Clock signal, while the row controller is clocked by the ClockPrime signal generated by the sequence controller. Both controllers have identical asynchronous-reset-synchronous-set logic for resetting shown in Figure 3.21. When the Reset signal is asserted high, ResetPrime is de-asserted resetting the shift register and logic block. This causes an asynchronous reset of the digital controller. While the Reset signal is high, FF1 will hold the Reset signal and FF3 will hold the ResetPrime signal when the Clock signal pulses. This synchronizes the Reset signal to the Clock signal to allow for a synchronous set of the digital controller. The FF3 and OR4 sets the shift register into its starting state after the Reset signal de-asserts.

An issue with the digital circuitry presented is that the clock signal, ClockPrime, for the row controller is generated by the sequence controller. When the Reset signal is asserted, this resets the sequence controller meaning the ClockPrime signal is not generated. Since the asynchronous-reset-synchronous-set logic requires a clock signal for FF1 and FF3, the row controller never properly restarts. This issue was not discovered until after fabrication. Fortunately a work around was found to mitigate this issue, which will be discussed in Section 4.3.

A small section of layout of the digital control blocks is shown in Figure 3.22. The sequence controller is located close to the reference diode since most of the tasks are operating on the reference diode to generate the reference voltage. The row controller however extends down the sense diode array and the row/word lines (W0, W1, ... , W15) extend across its respective row of sense diodes. A double guard ring encloses the two digital control blocks to reduce noise and isolate the digital logic from the diodes and analog circuitry.

Figure 3.20: A block diagram showing the connections between the sequence and row controller.

Figure 3.21: Asynchronous-reset-synchronous-set logic of both digital controllers.

Figure 3.22: Layout of digital control blocks.

3.6 Full Integrated Circuit

A detailed schematic of the alpha particle-detecting IC is shown in Figure 3.23. A simplified version of this schematic, only showing the sense and reference bit lines with one sense diode, is shown in Figure 3.24. A simulation of the full alpha particle detecting IC was performed with the simulation results shown in Figure 3.25. For ease of explanation, Figure 3.25 only shows results concerning sense diode 6. First, the signal $S_{refresh}$ is asserted which refreshes the bit line voltages, the selected sense diode, and the reference diode to $V_{bias} = 1.25$ V. Simultaneously the signal $S_{refresh}$ refreshes the bleeder capacitor back to 0 V. Next, the signal S_{ref} is asserted and the reference diode and bleeder capacitor are connected together resulting in a small amount of charge being removed from the reference diode. The signals S_{ref} and the selected word line S_{Wx} are asserted, connecting the sense and reference diodes to their respective bit lines. In this simulation, an alpha particle strikes sense diode 6 at time 1.1 ms, reducing the sense diode voltage to $V_{sense6} = 1.00$ V. When word line 6 is selected and signal S_{W6} is asserted, sense diode 6 is connected to the sense bit line resulting in a final voltage of $V_{senseBl} = 1.08$ V. The analog comparator then sees a differential voltage $V_{DIF} = 127$ mV between the sense bit line and the reference bit line. This result is fairly close to the theoretical 156 mV calculated by equation 3.7 and shown in Figure 3.10. Figure 3.25 also shows that $V_{DIF} = -31.6$ mV when no alpha particle has struck a sense diode, which is also close to the theoretical voltage from Figure 3.10.

Figure 3.23: Final schematic of the alpha particle-detecting CMOS IC.

Figure 3.24: Simplified version of final schematic, only showing the sense and reference bit lines with sense diode 6.

Figure 3.25: Simulation of final schematic, only showing the sense and reference bit lines with sense diode 6.

A layout of the final alpha particle detecting IC, excluding metal fill, is shown in Figure 3.26. The sensor is surrounded by a pad frame which includes buffers and ESD protection. This IC has separate power and ground pads for digital and analog circuitry, minimizing the coupling of noise from the digital circuitry into sensitive analog circuitry.

Figure 3.26: Complete alpha particle detecting IC layout.

Chapter 4

Alpha Particle-Detecting IC Testing

4.1 Analog Comparator Verification

Using an analog comparator test structure on the fabricated IC, a DC sweep was performed using a HP 4155 Semiconductor Parameter Analyzer as shown in Figure 4.1. The positive input of the comparator representing the voltage on the sense bit line was swept and the negative input was held constant at $V_{bias} = 1.25$ V. This measurement shows that the switching point of the analog comparator occurs at 1.245 V which is slightly less than simulated. Process variation could be responsible for the difference in switching point, however the calibration history of the HP 4155 used is unknown. Regardless, a switching point of 1.245 V means that the sense diode's voltage must change by 50 mV more than $V_{bleed} = 40$ mV, meaning that a theoretical voltage drop of 248 mV due to an alpha particle strike is still sufficient.

4.2 Diode Leakage Verification

The voltage drop in a sense diode due to leakage current was observed using a test structure on the IC which had an electrically floating sense diode reverse biased to 1.25 V and connected to a buffer amplifier. Using a microcontroller, a charge signal

Figure 4.1: Analog comparator's measured switching point.

was pulsed which charged the sense diode to $V_{bias} = 1.25$ V. The sense diode was then left to float for an extended period of time while the buffer amplifier output was measured using an oscilloscope. Figure 4.2 shows the sense diode's voltage dropping over 15 s, where after 1 second the sense diode voltage drops by 50 mV. Using an external clock of 100 kHz, the sense diodes only float for 960 μ s. If one approximates the first 1 s of sense diode leakage as linear, the sense diode will drop by about 50 μ V after 960 μ s. This amount of leakage is insignificant in comparison to V_{bleed} and V_{strike} .

4.3 Test Set-Up Using Alpha Particles

Since alpha particles can be stopped in a few centimeters of air, the alpha particle-detecting IC was tested in a vacuum chamber [4, 5]. The vacuum chamber used to verify the IC performance only has 10 external connections, while the IC has 16 outputs and requires additional control signals and voltage sources. To reduce

Figure 4.2: Measured leakage of a reverse biased floating sense diode.

external connections, the microcontroller was placed inside the chamber with the IC stacked on top, as shown in Figure 4.3. This reduced the number of external connections needed from 26 to 7, and allowed for the microcontroller to be completely re-programmable while inside the chamber. Additional support circuitry was attached to the top of the chamber and provided all the required voltages for the IC as well as organized the serial connections between the microcontroller and PC. The test set-up with the microcontroller and IC inside the vacuum chamber is shown in Figure 4.4.

For data acquisition, a MK20DX256VLH7 Cortex-M4 microcontroller (in a Teensy 3.1 prototyping board) was used to read data from the alpha particle-detecting IC. The microcontroller stores the location and number of alpha particle counts. In addition, the microcontroller counts the number of sequence controller cycles between alpha particle strikes, where one cycle has a period of $60 \mu\text{s}$ with a 100 kHz clock. Using software, the time between alpha particle strikes can be calculated. After an extended period of time, the microcontroller serially transmits the data to a PC.

Figure 4.3: Vacuum chamber lid used for tests involving alpha particle radiation.

Using software written in MATLAB, the received data is processed and displayed visually in real-time. The microcontroller also provides the clock and reset signals.

The support circuitry connected outside the vacuum chamber was used to organize all external voltage sources and serial connections to the vacuum chamber's coaxial connections. Initially, two HP E3630A voltage supplies, shown in Figure 4.4, were used to provide the power and reference voltage sources for the IC. However these voltage supplies were replaced with voltage regulators which were powered by either a HP E3630A voltage supply or a power adapter.

Figure 4.4: Vacuum chamber set-up used for tests involving alpha particle radiation.

As mentioned in Section 3.5, the reset circuitry on the IC does not reset correctly. This issue is largely overcome by not resetting the IC during operation, however some care had to be taken during start-up. To start the IC in the correct state, the reset signal is asserted and the external clock signal was fed into the IC with the power supplies turned off. After a few seconds, the power supplies are turned on and the microcontroller de-asserts the reset signal. The microcontroller monitors the IC's signals and notifies the user if the device has failed to start-up.

4.4 Response of a Sense Diode to an Alpha Particle Strike

The voltage drop in a sense diode due to an alpha particle strike was measured. The IC was placed 82 ± 1 mm from an uncalibrated 33.3 kBq americium-241 source in

Figure 4.5: Histogram of sense diode voltage drop after an alpha particle strike.

a vacuum chamber at 30 Pa. The pressure of the vacuum chamber was reduced to 30 Pa to ensure that the range of an alpha particles in air is significantly greater than the distance between the IC and americium-241 source [5]. This measurement was accomplished using a test structure on the IC which had an electrically floating sense diode reverse biased to 1.25 V and connected to a buffer amplifier. After measuring the voltage drop of 36 alpha particle strikes, a histogram was plotted in Figure 4.5 where the average voltage drop was measured to be 185 mV. This result is close to the theoretical 250 mV voltage drop calculated in Section 2.3. Figure 4.6 shows an example 200 mV voltage drop measured after an alpha particle struck the sense diode test structure.

4.5 Quantum Efficiency

Quantum efficiency is defined as the ratio between the number of measured counts by the alpha particle sensor to the number of expected alpha particle strikes on the

Figure 4.6: Response of single sense diode to an alpha particle strike.

surface of the IC [5]. The IC was placed 82 ± 1 mm from a 33.3 kBq americium-241 source in a vacuum chamber at 30 Pa. A quantum efficiency measurement of the alpha particle sensor was then conducted. The average expected number of alpha particle strikes on the surface of the IC is given by:

$$Counts = \frac{N \times A_{diode}}{4\pi r^2} \times Activity \times Time \quad (4.1)$$

where N is the number of sense diodes, A_{diode} is the surface area of one sense diode pn junction, and r is the distance from the americium-241 source [5]. From Equation 4.1, it is expected that an average of 60 ± 1 alpha particle counts would occur every minute. After 7.5 hours and more than 27 000 alpha particle counts recorded, a least squares fit to the data in Figure 4.7 produces an average count rate of 58.8 counts per minute. The quantum efficiency is therefore 98 ± 2 %, where the distance between the americium-241 source and IC is the largest known source of error.

Uncertainty may arise when two or more alpha particles strike the same sense diode within a sense interval, resulting in only one count being recorded. However the

Figure 4.7: Response of alpha-detecting CMOS IC to an americium-241 source in vacuum.

likelihood of multiple alpha strikes on one diode before it is compared and refreshed is very low. This is because the sense diode is compared and refreshed every $960\ \mu\text{s}$, whereas in the experiment described above a single sense diode would on average only receive an alpha strike every 4.3 minutes. In a typical radon measurement, even at high radon levels, the chance of multiple strikes on one sense diode prior to being refreshed is far less.

4.6 Monitor Design

The radon monitor from [4,5], was retro-fitted with the same microcontroller, support circuitry, and IC as used in the quantum efficiency test setup. However changes were made to the support circuitry board to allow for Bluetooth and for interfacing the microcontroller with the high voltage generating circuitry. The radon monitor is illustrated in Figure 4.8 and an annotated photo of the inside of the radon monitor is shown in Figure 4.9 below.

Figure 4.8: An illustration of the complete radon monitor with the alpha-detecting CMOS IC.

Figure 4.9: The complete radon monitor with the alpha-detecting CMOS IC. The electrostatic concentrator funnel is raised off the IC for clarity.

4.7 Radon Testing Using Radon Monitor

The radon monitor is powered by 18 V from a single HP E3630A voltage supply. Multiple voltage regulators (from 15 V to 1.25 V) are used to generate all required source and reference voltages for the alpha particle-detecting IC, microcontroller and high voltage generating circuitry. The radon monitor consumes 1.6 W of power, where 0.5 W and 0.72 W are used by the high voltage generator and the microcontroller respectively. The amount of power used could be considerably reduced by utilizing low power modes in the microcontroller and Bluetooth transceiver. An improved high voltage generating circuit might also reduce power consumption. A breakdown of the radon monitor power consumption is presented in Table 4.1.

Table 4.1: Radon Monitor Power Consumption Summary

Component	Power Consumed
Alpha Particle-Detecting IC	0.05 W
Microcontroller	0.72 W
Bluetooth	0.18 W
Support Circuitry	0.15 W
High Voltage Generator	0.5 W
Total	1.6 W

Prior to testing in elevated concentrations of radon, the monitor was left to run in a large 60 L sealed plastic container. The electrostatic concentrator was toggled on and off every 8 hours to check if it caused false alpha particle counts. After three days only two counts were detected.

Crushed rocks from an area known to contain low levels of naturally occurring uranium were then placed in the plastic container and left for two weeks until an equilibrium concentration of radon was achieved. A steady state radon concentration of approximately 1600 Bq/m^3 was measured using a Safety Siren Pro Series 3 radon gas detector by Family Safety Products Incorporated from Grandville, USA (<http://www.familysafetyproductsinc.com>). The accuracy of this detector is specified as $\pm 20 \%$ after 2 days [26]. Starting with the electrostatic concentrator on, a rate of 18 alpha particle counts per hour was recorded as shown in Figure 4.10. This rate can be normalized by 100 Bq/m^3 , giving a rate of 1.12 alpha particle counts per hour per 100 Bq/m^3 . It should be noted that only the alpha particles emitted towards the IC are detected. After about 8 hours the electrostatic concentrator was turned

off for 8 hours. While the electrostatic concentrator is off, no new polonium-218 will be collected onto the alpha sensor's surface. However all remaining radon progeny on the sensor's surface will still decay, so alpha strikes should continue to be recorded while the remaining polonium-218 and polonium-214 decay on the IC's surface. This behaviour is indeed seen in Figure 4.10. This was repeated 5 times, where the elapsed time and number of alpha particle counts while the electrostatic concentration was on is shown in Tables 4.2 and 4.4.

Table 4.2: Effective number of alpha particle counts and standard deviation after 2 days in 148 Bq/m³ of radon activity.

Measurement	Number of Counted Alpha Particles in 1,600 Bq/m ³ of Radon Activity	Elapsed Time (hours)	Counts per Hour in 1,600 Bq/m ³ of Radon Activity	Equivalent Counts per Hour in 148 Bq/m ³ of Radon Activity	Equivalent Counts per 2 Days in 148 Bq/m ³ of Radon Activity	Standard Deviation After 2 Days
1	149	7.92	18.4	1.70	81.7	9.04
2	168	7.62	22.1	2.04	98.1	9.90
3	115	7.95	14.5	1.34	64.4	8.02
4	133	7.85	16.9	1.56	75.0	8.66
5	121	6.92	17.5	1.62	77.7	8.81
Average:			17.9	1.65	79.4	8.89

Table 4.4: Effective number of alpha particle counts and standard deviation after 7 days in 148 Bq/m³ of radon activity.

Measurement	Number of Counted Alpha Particles in 1,600 Bq/m ³ of Radon Activity	Elapsed Time (hours)	Counts per Hour in 1,600 Bq/m ³ of Radon Activity	Equivalent Counts per Hour in 148 Bq/m ³ of Radon Activity	Equivalent Counts per 7 Days in 148 Bq/m ³ of Radon Activity	Standard Deviation After 7 Days
1	149	7.92	18.4	1.70	286	16.9
2	168	7.62	22.1	2.04	343	18.5
3	115	7.95	14.5	1.34	225	15.0
4	133	7.85	16.9	1.56	263	16.2
5	121	6.92	17.5	1.62	272	16.5
Average:			17.9	1.65	278	16.6

The radon monitor was also tested in the basement of a typical home in Ottawa, Canada where a radon concentration of 300 Bq/m³ was measured using a Ramon 2.2 radon monitor from GT Analytic SARL from Lambesc, France (<http://www.radon.at/engl/indexhtml.htm>), which has a specified accuracy of $\pm 3\%$ after 7 days [27]. A rate of 3.4 alpha particle counts per hour was recorded as seen in Figure 4.11.

Poisson statistics was used to determine the radon monitor's best case accuracy in an environment with 148 Bq/m³ radon activity (the EPA threshold for corrective measures [3]). The standard deviation of a Poisson distribution is [28]:

$$\sigma = \sqrt{\mu} \quad (4.2)$$

Where μ is the mean equivalent alpha particle counts per time. The accuracy of the radon monitor can be determined by:

$$\text{Accuracy} = \frac{\sigma}{\mu} \quad (4.3)$$

Therefore from Tables 4.2 and 4.4, Poisson statistics limit the radon monitor's best case accuracy in an environment with 148 Bq/m³ of radon activity to $\pm 11\%$ after 2 days and $\pm 6\%$ after 7 days. This is comparable to the stated accuracy of the existing Safety Siren Pro Series 3 and Ramon 2.2 consumer-level radon monitors. The accuracy could be improved by focusing more radon progeny onto the IC surface with an updated electrostatic concentrator design.

Figure 4.10: Total alpha particle counts recorded by monitor exposed to 1598 Bq/m³ radon activity. Electrostatic concentrator (EC) toggled on and off as indicated.

Figure 4.11: Total alpha particle counts detected by the radon monitor in a basement with 300 Bq/m³ radon activity.

Chapter 5

Conclusions and Future Work

A radon monitor using a custom CMOS IC to detect alpha particles emitted from electrostatically collected radon progeny is reported. The alpha particle-detecting IC consisting of a 16×16 array of reverse biased *pn* junction diodes was fabricated using a foundry CMOS process to allow for low cost mass production.

Testing of the IC revealed that on average a 185 mV voltage drop occurred in a reverse biased diode after an alpha particle strike, which is close to theoretical estimates. Quantum efficiency measurements showed that the IC had a 98 ± 2 % efficiency.

The radon monitor consumes 1.6 W of power, with the high voltage generating circuitry and microcontroller consuming the most power. The monitor demonstrated a steady-state sensitivity of 1.12 counts per hour per 100 Bq/m³ of radon activity. The monitor was also tested in a home environment representative of typical expected consumer use, where it detected 3.4 counts per hour at a radon concentration of 300 Bq/m³. Poisson statistics limit the radon monitor's accuracy to $\pm 11\%$ after 2 days and $\pm 6\%$ after 7 days in an environment with 148 Bq/m³ of radon activity. This is comparable to the stated accuracy of the existing consumer-level radon monitors. This radon monitor prototype appears to be an inexpensive consumer grade solution for radon gas detection that could be easily adopted in homes.

In future work, the asynchronous-reset-synchronous-set logic needs to be corrected for a reliable consumer grade product. Improvements to the high voltage generating circuit and the electrostatic concentrator are planned to reduce power consumption and to increase collection efficiency of radon progeny. Improvements in the micro-controller system are necessary for a consumer grade product. Calibration of the radon monitor, with an analysis of the effects of temperature, humidity, and airborne particulates will be essential for accurate radon activity measurements.

List of References

- [1] H. Zeeb and F. Shannoun, Eds., *WHO Handbook on Indoor Radon: A Public Health Perspective*. Geneva, Switzerland: WHO Press, 2009.
- [2] Health Canada. (2014) International Radon Project: Survey on Radon Guidelines, Programmes and Activities. http://www.hc-sc.gc.ca/ewh-semt/alt_formats/pdf/pubs/radiation/radon_canadians-canadiens/radon_canadians-canadien-eng.pdf.
- [3] United States Environmental Protection Agency. (2012) A citizen's guide to radon: The guide to protecting yourself and your family from radon. EPA 402-K-07-009. <http://www.epa.gov/radon/pdfs/citizensguide.pdf>.
- [4] R. H. Griffin, H. Le, D. T. Jack, A. Kochermin, and N. G. Tarr, "Radon monitor using custom alpha-detecting MOS IC," in *Sensors, 2008 IEEE*, Oct 2008, pp. 906–909.
- [5] R.H. Griffin, "Radon Monitor using Custom alpha-detecting MOS Integrated Circuit," Master's thesis, Department of Electronics, Carleton University, 2008.
- [6] A. Ross, R. Griffin, and N. Tarr, "Radon monitor using Alpha-Detecting CMOS IC," in *Sensors Applications Symposium, 2016 IEEE*, March 2016, to be published.
- [7] C.M. Lederer, J.M Hollander, and I. Perlman, *Table of Isotopes*, 6th ed. New York: John Wiley and Sons, Inc., 1968.
- [8] National Cancer Institute. (2010) National Cancer Institute's 2010 Surveillance, Epidemiology, and End Results (SEER) estimated US mortality numbers. http://seer.cancer.gov/archive/csr/1975-2007/results_single/sect.01_table.01.pdf.
- [9] Health Canada. (2012) Cross-Canada Survey of Radon Concentrations in Homes, Final Report. http://www.hc-sc.gc.ca/ewh-semt/alt_formats/pdf/radiation/radon/survey-sondage-eng.pdf.

- [10] G. Knoll, *Radiation Detection and Measurement*, 2nd ed. New York: John Wiley and Sons, 1989.
- [11] R. D. Bolton, "Radon monitoring using long-range alpha detector-based technology," in *Nuclear Science Symposium and Medical Imaging Conference, 1994., 1994 IEEE Conference Record*, vol. 2, Oct 1994, pp. 940–944.
- [12] B. Nodari, M. Caldara, V. Re, and L. Fabris, "Radon fast detection and environmental monitoring with a portable wireless system," in *2015 6th IEEE International Workshop on Advances in Sensors and Interfaces (IWASI)*, June 2015, pp. 254–259.
- [13] G. Batignani, S. Bettarini, M. Bondioli, M. Boscardin, L. Bosisio, G. F. D. Betta, S. Dittongo, F. Forti, G. Giacomini, M. A. Giorgi, P. Gregori, C. Piemonte, I. Rachevskaia, S. Ronchin, and N. Zorzi, "Functional characterization of a high-gain BJT radiation detector," *IEEE Transactions on Nuclear Science*, vol. 52, no. 5, pp. 1882–1886, Oct 2005.
- [14] C. M. Hsieh, P. C. Murley, and R. R. O'Brien, "A field-funneling effect on the collection of alpha-particle-generated carriers in silicon devices," *IEEE Electron Device Letters*, vol. 2, no. 4, pp. 103–105, April 1981.
- [15] J. Baker, *CMOS Circuit Design, Layout, and Simulation*, 3rd ed. Piscataway, NJ: IEEE Press, 2010.
- [16] R. C. Baumann, "Radiation-induced soft errors in advanced semiconductor technologies," *IEEE Transactions on Device and Materials Reliability*, vol. 5, no. 3, pp. 305–316, Sept 2005.
- [17] J. L. Autran, S. Serre, S. Semikh, D. Munteanu, G. Gasiot, and P. Roche, "Soft-Error Rate Induced by Thermal and Low Energy Neutrons in 40 nm SRAMs," *IEEE Transactions on Nuclear Science*, vol. 59, no. 6, pp. 2658–2665, Dec 2012.
- [18] M. S. Gordon, P. Goldhagen, K. P. Rodbell, T. H. Zabel, H. H. K. Tang, J. M. Clem, and P. Bailey, "Measurement of the flux and energy spectrum of cosmic-ray induced neutrons on the ground," *IEEE Transactions on Nuclear Science*, vol. 51, no. 6, pp. 3427–3434, Dec 2004.
- [19] R. H. Griffin, H. Le, D. T. Jack, and N. G. Tarr, "Alpha-RAM: An alpha particle detecting MOS IC for radon monitoring," in *Microsystems and Nanoelectronics Research Conference, 2008. MNRC 2008. 1st*, Oct 2008, pp. 73–76.

- [20] R. Griffin, “Radon detector,” 2006, Fourth Year Engineering Project Report, Carleton University, Dept. of Electronics, Unpublished.
- [21] A. Miles, R. Griffin, Y. Shen, and N. Tarr, “A wireless solution for radon gas detection,” in *Microsystems and Nanoelectronics Research Conference, 2009. MNRC 2009*, Oct 2009, pp. 88–91.
- [22] R. Griffin and N. Tarr, “Optical image sensors and their application in radon detection,” *Proc. SPIE 8915, Photonics North*, vol. 8915, 2013.
- [23] R. H. Griffin, A. Kochermin, N. G. Tarr, H. McIntosh, H. Ding, J. Weber, and R. Falcomer, “Sensitive, fast-responding passive electrostatic radon monitor,” in *Sensors, 2011 IEEE*, Oct 2011, pp. 1074–1077.
- [24] H. Miyake and K. Oda, “Portable and High-Sensitive Apparatus for Measurement of Environmental Radon Using CR-39 Track Detector,” *Jap. J. Appl. Phys.*, vol. 26, pp. 607–610, 1987.
- [25] S.M. Sze, and K.K. Ng, *Physics of Semiconductor Devices*. Hoboken, US: Wiley-Interscience, 2006.
- [26] *Pro Series3 Radon Gas Detector HS71512*, Sylvane, Roswell, GA.
- [27] *Ramon 2.2 Radon-Monitor*, GT-Analytic SARL, Lambesc, France.
- [28] P. Bevington and D. Robinson, *Data reduction and error analysis for the physical sciences*, 2nd ed. New York: McGraw-Hill, 1992.