# Optical image sensors and their application in radon detection

Ryan H. Griffin and N. Garry Tarr

Department of Electronics, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6

# ABSTRACT

This paper reports on the development and testing of a direct reading radon detector assembled from consumer electronics at very low cost. An electrostatic concentrator constructed by metalizing a plastic funnel is used to focus charged radon progeny onto the exposed surface of an optical image sensor from a webcam. Alpha particles emitted by the collected progeny strike the image sensor, generating sufficient charge to completely saturate one or more pixels. The high voltage required by the concentrator is generated using a simple Cockcroft-Walton charge pump. A personal computer is used to analyze the webcam data. Alpha particles were counted at a rate of 5.2 counts/hour at a radon concentration of 159  $Bq/m^3$ .

Keywords: Radon monitor, passive, direct reading, electrostatic concentration, CMOS, image sensor, webcam

# 1. INTRODUCTION

Radon ( $^{222}$ Rn) is the second leading cause of lung cancer. In the U.S. the Environmental Protection Agency (EPA) attributes 21,000 deaths per year to radon exposure.<sup>1,2</sup> The World Health Organization (WHO) states that 3-15% of all lung cancers are caused by radon.<sup>3,4</sup> Produced from the decay of naturally occurring uranium, radon readily diffuses to the earth's surface where it may become trapped in buildings. Monitoring of indoor radon concentrations is recommended to determine if mitigation is necessary. As radon concentrations may vary rapidly, it is desirable to have a fast responding direct reading detector. Health Canada has set a suggested action level for mitigation at activities above 200 Bq/m<sup>3</sup> while the EPA and WHO have set suggested action levels of 150 Bq/m<sup>3</sup> and 100 Bq/m<sup>3</sup> respectively.

Direct reading radon detectors are commercially available but vary wildly in performance and cost. This paper reports on the development and testing of a direct reading radon detector assembled from consumer electronics at very low cost. An electrostatic concentrator constructed by metalizing a plastic funnel is used to focus charged radon progeny onto the exposed surface of an optical image sensor from a webcam. Alpha particles emitted by the collected progeny strike the imager, generating sufficient charge to completely saturate one or more pixels. The high voltage ( $\sim 1000 \text{ V}$ ) required by the concentrator is generated using a simple Cockcroft-Walton charge pump. A personal computer (PC) is used to analyze the webcam data.

Details on the radon decay chain, and the health effects of radon, are available in more detail elsewhere. $^{1-5}$ 

# 2. DESIGN

In order to improve the response time of radon detectors, it is desirable to concentrate radon and radon progeny near a radiation detector. Either active or passive concentration may be used. Active systems increase the sampling volume of air by means of pumps or fans. These systems offer fast response, but are prone to problems with pump reliability and calibration, and are generally not practical for extended use with battery power supplies.<sup>6</sup> Passive systems utilize the charged nature of radon progeny<sup>7</sup> to concentrate progeny near a detector. Passive systems may not offer the fast response of active systems, but their simplicity and cost effectiveness are attractive in assembling a home radon monitor.

Further author information: (Send correspondence to N.G.T.)

Photonics North 2013, Pavel Cheben, Jens Schmid, Caroline Boudoux, Lawrence R. Chen, André Delâge, Siegfried Janz, Raman Kashyap, David J. Lockwood, Hans-Peter Loock, Zetian Mi, Eds., Proc. of SPIE Vol. 8915, 89151C · © 2013 SPIE · CCC code: 0277-786X/13/\$18 · doi: 10.1117/12.2033635

N.G.T.: E-mail: ngt@doe.carleton.ca, Telephone: 1 613 520 5758

R.H.G.: E-mail: rgriffin@doe.carleton.ca, Telephone: 1 613 520 2600 x8339



Figure 1. Radon detector prototype. The housing is a black ventilated electronics project box. The electrostatic concentrator, high voltage generator and webcam radiation detector are outlined in red, orange and yellow respectively.

Detecting the emissions from decaying progeny can be achieved with a wide array of detectors.<sup>8</sup> Silicon diode detectors are desirable due to their direct reading nature. A modern image sensor is effectively an array of silicon diode detectors optimized to detect light. With a few modifications an off-the-shelf webcam can make a cost effective  $\alpha$  particle radiation detector.

Figure 1 presents an image of the radon detector developed using readily available consumer parts. The housing is a black ventilated electronics project box. Black is a desirable colour for reducing the probability of stray light reflecting onto the image sensor. Ventilation is required such that the radon concentration in the interior of the housing comes into equilibrium with the test area. Details on the design of the electrostatic concentrator and high voltage generator, as well as details on the image sensor configuration are found in the subsections which follow.

# 2.1 Electrostatic Concentrator

A two-electrode cone shaped electrostatic concentrator was fashioned from a Nalgene powder funnel. Details about the funnel and its dimensions can be found in Table 1.

Thermoscientific Nalgene model number	4252-0100
Capacity	243  mL
Overall height	$106 \mathrm{~mm}$
Stem diameter	21 mm
Stem length	$33 \mathrm{~mm}$
Top inner diameter	104 mm

Table 1. Electrostatic concentrator funnel details and dimensions.

Metalization of the electrostatic concentrator walls was achieved using 32  $\mu$ m thick self-adhesive copper tape. The lower electrode height and electrode gap are both 15 mm. A copper mesh forms the concentrator top. Figure 2 presents the funnel before and after metalization. Note the funnel stem has been removed.



Figure 2. Electrostatic concentrator before (a) and after (b) metalization. Contour: Electric field norm (V/m) Streamline: Electric field



Figure 3. Electrostatic concentrator simulation showing electric field lines and contours of electric field strength.

Figure 3 presents 2D axially symmetric COMSOL simulation of the electrostatic concentrator. In these simulations the image sensor and PCB are held at 0 V while the upper and lower electrodes are set to 1400 V and 1000 V respectively. Shown are contours of electric field strength in the concentrator as well as the electric field lines spanning the IC. Charged radon progeny travels along these electric field lines and is deposited on the image sensor surface for detection. A minimum electric field strength of 50 V/m should be acceptable for charged progeny collection.<sup>9</sup>

# 2.2 High Voltage Generation

A bipolar 555 timer is used to drive a Triad Magnetics SP-4 audio transformer in order to provide an initial voltage step-up. The audio transformer then drives a 12 stage Cockcroft-Walton charge pump. Two connections to the charge pump are made in stages 8 and 12 in order to drive the upper and lower concentrator electrodes respectively. Using a 15 V supply the upper and lower concentrator are driven to 1370 V and 986 V respectively. Figure 4 presents the circuit schematic and a photo of the circuit implementation.



Figure 4. Cockcroft-Walton high voltage generator schematic (a) and implementation (b).

#### 2.3 CMOS Imager

As radon, and its progeny, decays it will emit a series of  $\alpha$  and  $\beta$  particles. Both types of particles can be detected using silicon diode detectors. However,  $\alpha$  particles have a much higher linear energy transfer (LET) and are generally easier to detect. In this work a webcam image sensor is used to detect the  $\alpha$  emissions from radon progeny, in particular, <sup>218</sup>Po and <sup>214</sup>Po which have been concentrated onto the image sensor surface.

It was necessary to modify the webcam in order to make it sensitive to  $\alpha$  particle radiation. The image sensor packaging coverglass, which would otherwise have absorbed any  $\alpha$  emissions incident on the image sensor, was removed.<sup>8</sup> Additionally a larger access opening was cut into the webcam case and the LED which indicates when the webcam is active was covered. Figure 5 presents images of an unmodified and modified Microsoft VX-2000 webcam. Although no power dissipation measurements were made, Microsoft Windows Device Manager indicates that the webcam request 500 mA of current from the Universal Serial Bus (USB). Approximate dimensions of the active area of the image sensor are 4 mm  $\times$  3 mm.



Figure 5. Original (a) and modified (b) Microsoft VX-2000 webcam used for  $\alpha$  particle detection.

# **3. ANALYSIS METHOD**

Webcam control and analysis routines were written in MATLAB using the image acquisition and image processing toolboxes. Data was read in 50 frames at a time and then analyzed. Each frame was set to the longest possible exposure. Although the exposure time was set to 1.95 ms, an exposure time of 155 ms was observed. The amount of time required to record each batch of frames, and the amount of time required to analyze each batch was also recorded. This allows a rough estimate of sensor dead time to be made.

Each frame was then converted into a binary image. A threshold of 75% of the maximum analog to digital conversion (ADC) value for a pixel was used to determine if a pixel had interacted with an  $\alpha$  particle. Instead of analyzing each frame independently all 50 binary frames were summed together to reduce the amount of processing time required. Pixels, or clusters of pixels, were then counted on the binary image representing the sum of all 50 frames.

Using the personal computer's clock as a reference, data including date, time, exposure time, analysis time, number of clusters counted, and the address of each pixel in a given cluster, was all recorded into a text file for later analysis.

#### 4. RESULTS

Measurement results using the prototype radon detector are seen in Figures 6 and 7 respectively. A Safety Siren<sup>10</sup> radon monitor was used as a reference and recorded an average radon concentration of 159 Bq/m<sup>3</sup> during these experiments. Figure 6 demonstrates the effects of switching the high voltage electrostatic concentrator on and off. Figure 7 presents data from a longer run and shows the distribution of  $\alpha$  strikes over the image sensor surface. A least squares fit to the data in Figure 7(a) with the concentrator on yields a count rate of 5.2 counts per hour at 159 Bq/m<sup>3</sup>. A discussion of these results follows.



Figure 6. Measurement results showing the effect of switching the high voltage electrostatic concentrator on and off (a). Also shown is a histogram presenting data on pixel cluster sizes due to the interaction of an  $\alpha$  particle on a Microsoft VX-2000 webcam (b).

#### 5. DISCUSSION

Measurement results indicate that the electrostatic concentrator was able to deposit charged radon progeny onto the exposed image sensor. However, the deposition pattern seen in Figure 7(b) indicates that more concentrator optimization could be done. Increased detector sensitivity could be had by collecting a larger volume of radon progeny onto the image sensor surface. This result is further supported by the simulation shown in Figure 3 where the electric field lines pointing towards the surface of the IC show only a small fraction of the charged



Figure 7. Measurement results showing  $\alpha$  particle counts as a function of time (a) as well as the position of interactions on the image sensor surface (b).

progeny in the concentrator volume would be deposited on the sensor. By optimizing the concentrator shape, electrode size/spacing, and applied potential, a larger volume of charged progeny could be collected.

Simulations, and experimental validation, have been preformed on a similar detector and it was shown that a turn on transient of 1.44 hours would be required for the detector to reach 90% of its peak counting rate.<sup>11</sup> These simulations are inclusive of the fact that only 88% of <sup>218</sup>Po is charged after the decay of <sup>222</sup>Rn.<sup>7</sup> Also note that progeny emit radiation isotropically and only radiation emitted towards the IC will be detected. When an isotope emits an  $\alpha$  towards the image sensor, there is sufficient recoil energy to eject the decay product from the sensor surface and this reduces the probability of detection of any subsequent  $\alpha$  particles. The turn-off transient of this radon detector is government by the decay of  $\alpha$  emitting progeny on the sensor surface inclusive of intermediate isotopes.<sup>12</sup>

Some background counts are to be expected. Without the concentrator, the image sensor could record  $\alpha$  emissions within an approximate 4 cm hemisphere over its surface. Enabling the concentrator allows radon progeny to be sampled from a larger volume and increases the likelihood of detection. As expected there is an appreciable count rate increase with the concentrator enabled.

Histogram data in Figure 6(b) indicates a number of small clusters. Given that many more pixels are typically involved in an  $\alpha$  strike, it is possible that these small clusters are actually false counts and should be filtered from the data. It is also possible that the small cluster size events are due to interaction with  $\beta$  particles from other isotopes in the radon decay sequence. Despite using a large threshold for detection, the webcam image sensor was seen to be weakly sensitive to  $\beta$  particles. Exposing the image sensor to a <sup>90</sup>Sr source showed a number of activated pixels. The mean pixel cluster size for  $\beta$  particle interaction from the <sup>90</sup>Sr source was found to be 1.1 pixels when using a detection threshold of 75%. The quantum efficiency of the detector to  $\beta$  particles was not determined in these measurements. When the threshold for detection was increased from 75% to 100%, no pixels were activated by the <sup>90</sup>Sr source. It may be possible to improve the sensitivity of the detector by optimizing the threshold for detection to allow  $\beta$  emissions to be detected while maintaining a sufficient signal to noise ratio (SNR).

An analysis of the data showed that the MATLAB routine spent approximately 2.5% of the total running time analyzing data and 97.5% of the time capturing and reading data from the webcam.

#### 6. CONCLUSION

A prototype radon detector has been made using readily available consumer parts. Progeny concentration has been achieved using an electrostatic concentrator, while  $\alpha$  particles were detected using a CMOS webcam. In a radon ambient of 159 Bq/m<sup>3</sup> a measured count rate of 5.2 counts/hour was observed.

#### REFERENCES

- Environmental Protection Agency, [EPA Assessment of Risks from Radon in Homes], EPA Air and Radiation 402-R-03-003, Washington (2003).
- [2] Environmental Protection Agency, [A Citizen's Guide to Radon], EPA Indoor Air Quality 402/K-12/002, Washington (2012).
- [3] World Health Organization, [International Radon Project Leaflet], WHO Press, Geneva (2006).
- [4] World Health Organization, [Handbook on Indoor Radon], WHO Press, Geneva (2009).
- [5] Committee on Health Risks of Exposure to Radon (BEIR VI), N. R. C., [Health Effects of Exposure to Radon:BEIR VI], The National Academies Press, Washington D.C. (1999).
- [6] Bigu, J. and Raz, R., "Passive radon/thoron personal dosimeter using an electrostatic concentrator and a diffused-junction detector," *Rev. Sci. Instrum.* 56, 146–153 (Jan. 1985).
- [7] Chu, K.-D. and Hopke, P., "Neutralization kinetics for polonium-218," Environmental Science and Technology 2(6), 711-717 (1988).
- [8] Knoll, G., [Radiation Detection and Measurement 2nd Ed.], John Wiley and Sons, New York, NY (1989).
- [9] Miyake, H., Oda, K., and Michijima, M., "Portable and High-Sensitive Apparatus for Measurement of Environmental Radon Using CR-39 Track Detector," *Journal of Applied Physics* **26**(4), 607–610 (1987).
- [10] Family Safety Products Incorporated, "Safety Siren Pro Series 3 Radon Gas Detector."
- [11] Griffin, R. H., Kochermin, A., Tarr, N. G., McIntosh, H., Ding, H., Weber, J., and Falcomer, R., "Sensitive, fast-responding passive electrostatic radon monitor," in [*Proc. IEEE Sensors 2011*], 1074–1077 (2011).
- [12] Griffin, R. H., Le, H., Jack, D. T., Kochermin, A., and Tarr, N. G., "Radon monitor using custom alphadetecting MOS IC," in [*Proc. IEEE Sensors 2008*], 906–909 (2008).