Alpha particle spectrometry with CMOS webcam and a SBC

R. Hashemzadeh[1], S. Ashrafi[1*], H. Naghshara[1] and H. Kasani[1]

[1]Faculty of Physics, University of Tabriz
Email addresses: rhashem@tabrizu.ac.ir, ashrafi@tabrizu.ac.ir, naghshara@tabrizu.ac.ir, Hadi.kasani@tabrizu.ac.ir
[*]Corresponding author
Received: 2020-01-27
Revised: 2020-03-12
Accepted: 2020-05-25

Abstract
We present the development of a system for the detection and energy spectrometry of alpha particle radiation based on the Commercial Off The Shelf (COTS) CMOS image sensor. The data is read, processed and displayed in real-time using a single-board-computer (SBC). We show that by using image processing techniques, a slightly modified webcam can be used to measure α radiation. In contrast to dedicated measurement devices such as Geiger counters, our framework can classify the type of radiation and can differentiate between various kinds of ionizing radiation. The system was tested with standard ^{226}Ra and ^{241}Am alpha sources.

Keywords
Webcam, CMOS image sensor, Alpha particle, single-board-computer (SBC), image processing.

1. Introduction

The Complementary Metal-Oxide Semiconductor (CMOS) image sensors convert light into electric charge. The light interacts with silicon semiconductor in photodiode through photoelectric effect. The charge created in each pixel is then processed into electronic signals.

There are numerous recent studies, on radiation effects in the CMOS image sensors, suggesting that the commercial off the shelf (COTS) webcams which are equipped with a CMOS sensor can be used for: X-ray radiography [1-5], γ-ray spectrometry [6-7] and electron microscopy [8-10] applications. However, only a few studies discuss α-particle detection [11-12]. A CMOS radon detector based on counting the alpha particle emitted from radon progenies, ^{218}Po and ^{214}Po, has been reported [13-16]. They have shown that a count rate of 5.2 hr^{-1} at radon concentration of 159 Bq/m3 can be achieved by means of an electrostatic concentrator which focuses radon progeny on the CMOS image sensor of a low-cost webcam.

To detect the heavy charged particles by a CMOS, small modifications in the webcam have to be made. Several hundreds of microns thick protective glass is usually placed on the CMOS image sensor. Although the attenuation of the X-ray and γ-ray in this glass layer is negligible, the energy loss of the charged particle in this layer is significant and therefore, it is necessary to remove the glass layer. This is especially crucial to α-particle detection, where the linear energy transfer (LET) is high.

Geiger counters are currently one of the most commonly used devices for measuring radiation flux in the field. Although these counters can detect alpha, beta particles and gamma rays, but they can neither measure the energy of the particles nor specify their type, features which require extremely expensive equipment. On the other hand, a modified CMOS webcam can classify the type of radiation and can differentiate between various kinds of radioactive materials.

The results of the comparison of Geiger and Webcam detector performance in alpha particle detection are reported in ref [7]. In the first experiment, a 33 kBq ^{241}Am source was used. The web camera detected 47 ± 2 particles per second. Commercial Geiger-Müller counter Eko-C detected only 22 ± 1 particle per second. This difference signifies that an explored image sensor has got twice bigger sensitivity for this energy of alpha particle. It could be caused by the fact that some particles were absorbed by a mica window of the Geiger tube. Another reason for the high sensitivity of the webcam is the fact that the high density of silicon increases the intrinsic detection efficiency of the webcam. Experiments with a plane source were very similar: ^{239}Pu and ^{241}Am with a plane radioactive activity 4.19 Bq/cm^2 and 16.53 Bq/cm^2.

In this work, we show that by slightly modifying the image sensor, an inexpensive and commercial off-the-shelf webcam can be used as a portable alpha radiation detector. By connecting the CMOS imager to a Raspberry pi 3B SOC model single-board-computer (SBC) and a 3.5 inch Touch Screen, the sensor would be capable of displaying alpha particle counts and spectrum online. The obvious advantages of the CMOS alpha particle detector are low price, low power consumption, high spatial resolution and real-time data acquisition and image processing.

2. Material and methods

2.1. Interaction of α particle with a CMOS image sensor

Webcams are composed of a set of light sensing elements (pixels) arranged in a regular matrix and optimized to detect the visible range of light at 30 to 60 frames per

second. As shown in Figure 1, each pixel includes a photodiode (PD) which acts as light sensor and three nMOS transistors: reset transistor (M_{RS}), source follower transistor (MSF) and row select transistor (M_{SEL}).
If a charged particle enters into a pixel, several hundreds of electron-hole pairs will be generated along the interaction path. On average 3.6 eV needed to generate an electron-hole pair in silicon [17], so a 5.5 MeV α particle can produce approximately 1.5 million electron-hole pairs within 2-3 µm of the alpha particle track. If the electron-hole pairs are formed in the depletion region of the photodiode, then they are swept away by the internal electric field, thus creating a drift current. If the pairs are created in the n-type region, the electrons will remain, and the holes are left to diffuse toward the depletion region. If the pairs are created in the p-type region, the holes will remain, and the electrons will diffuse toward the depletion region. Thus, the total current in the photodiode is the addition of the diffusion and the drift currents [18-23]. The collected charges are converted into a voltage on the photodiode junction capacitance C_{PD} while the reset transistor is OFF

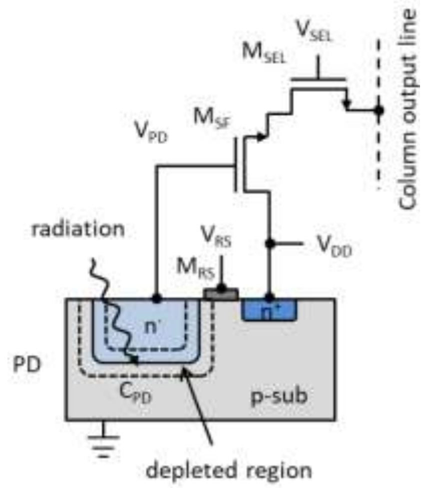

Fig. 1 Schematic figure of photodiode pixel.

The accumulated charge decreases the potential in the PD (V_{PD}) according to the input light intensity. After an accumulation time (33 *msec* at video rate) the select transistor M_{SEL} is turned on and the output signal in the pixel is transmitted to the source follower transistor M_{SF} which acts as a buffer amplifier. When the read-out process is carried out, M_{SEL} is turned off and M_{RS} is again turned on to repeat the above process. In the readout circuit the amplifier converts the charge originated in the photodiode into a voltage that is read, pixel by pixel, and subsequently digitized into a numerical value ranging from 0 to 255. When the Full Well Capacity (FWC) of individual photodiodes, or the maximum charge transfer capability of the sensor is reached, the pixel becomes saturated and the excess charge naturally overflow to the potential wells of adjacent pixels. This effect, known as blooming, spreads the electric charges created by the alpha particle collision in a circular region of several pixels radius.

2.2 Webcam modification

2.2.1. Removing protective glass

The pathway and range of charged particles in matter depends on the type of particle, the energy of the particle, and the material of the absorber. Alpha particles are heavier than electrons and protons, so their path is relatively straight. The linear energy transfer (LET) of the alpha particles is much greater than that of β particles and protons. For example, in silicon, the LET value of a 5.5 MeV alpha particle emitted from ^{241}Am is 0.58 MeV/mg/cm^2, and the particle would stop in 27 µm [24].

Figure 2 schematically shows the components of a CMOS sensor. For an alpha particle to be detected in the CMOS photodiode, it must be able to pass through the 560 µm protective glass, 3.9 µm colour filter, 4 µm microlens and 4 µm silicon oxide insulator layers [25]. For high penetrating particles such as beta particles and photons, the attenuation in the glass is relatively low, and thus the protective glass is not a critical or limiting factor. However, the glass layer is the main obstacle for the particles to reach the photodiode and actually stops the alpha particles.
Removing the protective glass layer is difficult and possible only for some kinds of sensors. The image sensor is located behind a protective glass plate and is connected to the rest of the electronics by a set of fine wires around the edge of the sensor. There are two methods for removing the protective glass. In first method, the glass cover is removed by using a hot plate to soften the glue. The glass of the sensor is placed directly onto the hot plate which is set to 85 °C. Once the glue had softened the glass is removed using a scalpel. In second method, the glass cover is removed by shattering the glass and carefully removing any shards that fall on the sensor. To remove shards, one can use a dry cotton swab followed with a cotton swab soaked in ethyl alcohol to gently remove as many remaining shards off the sensor as possible.
In this work, to ensure the imager sensitivity to alpha particles, the glass layer was removed by using a hot air blower to soften the adhesive that held them in place. Once the adhesive had softened, the glass was removed using a scalpel.

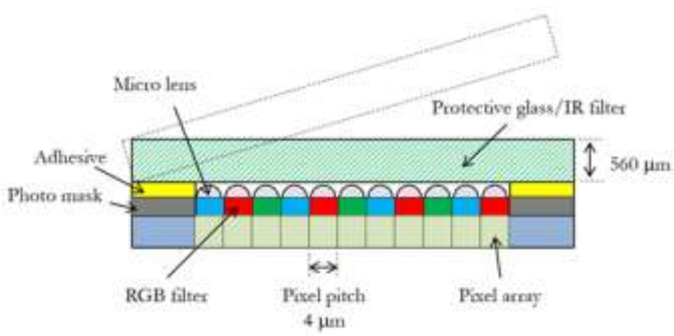

Fig. 2 The various components of the CMOS sensor are shown

The most important specifications of the webcam are listed in Table I.

2.2.2. Aluminium layer deposition

Since the protective glass we removed is an IR/UV reflective dichroic coating on the glass, removing it also makes the webcam sensitive to infrared and ultraviolet light. Therefore, to replace the IR filter and to remove the possible optical influences we deposited a thin Al layer on the sensor.

Table I. CMOS Sensor specifications [26]

Sensor Dimension	3.5 mm × 2.7 mm
Sensor area	9.45 mm^2
Pixel size	2.8 µm × 2.8 µm
Resolution	1280 × 960
Image Resolution	640 × 480
Frame Rate	30 fps @ 640×480

In the CMOS sensor, the radiation-sensitive area is composed of a large number of pixels of ~3 µm. When it comes to particle tracking, this pixilation would be a big advantage because it increases the spatial resolution of the detector. In all previous studies [2, 28], a thin aluminium foil has been used to cover the sensor. However, this is not a good solution to isolate the sensor from the ambient light. A number of alpha particles are deflected by large angles (> 4°) as they passed through the aluminium foil. Any space between foil and sensor would lead to a loss of spatial resolution. But in case of layer deposition, there is no gap between the aluminium thin layer and the sensor and the spatial resolution is not lost.

Moreover, the layer should be thin enough to prevent light from reaching the sensor but, at the same time, should not be thick enough to greatly reduce the energy of the alpha particles. In previous works [2,28], they have not paid much attention to determining the appropriate foil thickness and wrapped the sensor with 5 µm [2] and 8 µm [28] aluminium sheets. We have used Monte Carlo simulation and found that optimum thickness of the aluminium layer should be 200 nm.

A thin (200 nm) aluminium layer was deposited on the modified CMOS sensor of a webcam by thermal evaporation using the vacuum coating unit model 15F6 (manufactured by Hind High. Vacuum Co. (P) Ltd., Bangalore, India.). The distance from the source to the substrate was 12 cm. To prevent unwanted evaporation of plastic from the webcam attachments, all parts except the CMOS sensor were covered with aluminium foil.

To properly select the coating area, a mask of the same type of aluminium foil was carefully cut and glued to the CMOS (see Figure 3). The crucible was a tungsten basket on which the pieces of aluminium wire hang. The aluminium wire used for evaporation was of the blazers materials type with a purity of 99.98 % and a diameter of 1 mm. Before Al deposition, the vacuum chamber pressure was reduced down to 5.0×10^{-5} mbar. A vibrating quartz crystal was used to control the thickness of the aluminium layer with one angstrom precision. After layer deposition, the substrate was kept in vacuum chamber for half an hour and then ventilated with nitrogen gas.

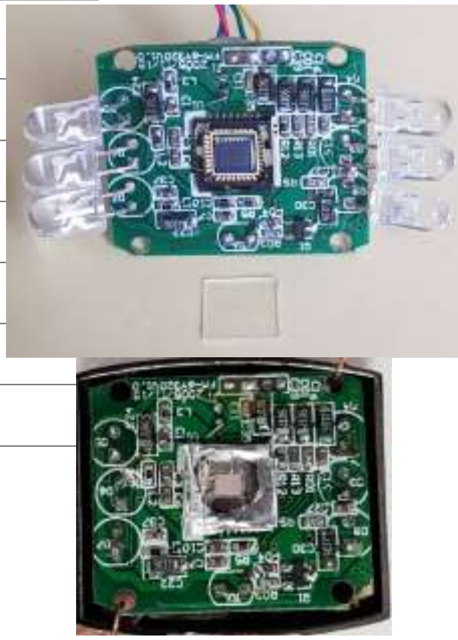

Fig. 3 Modified webcam: (top) the protective glass has been removed, (down) LEDs have been replaced with 1N4148 diodes and the sensor circuit has been covered with an aluminum mask before aluminum deposition.

2.3. Connecting webcam to SBC and LCD

The Raspberry Pi 3B is a tiny SBC and very cheap (35 USD) computer designed to help people learn programming. It provides a set of GPIO (general purpose input/output) pins that allow controlling electronic components for physical computing. A Raspberry Pi 3 Model B with a 1.2 GHz 64-bit quad core processor and Raspbian Linux operating system was used in this work.

To make the alpha particle detector portable, the USB webcam and a 5″ resistive touch Screen LCD (800×480 resolution) were connected to the Raspberry Pi through GPIO ports. Since the Raspberry Pi cannot power the webcam by itself, we have used an external USB hub with a commercial 1500 mAh 7.5Wh 5V DC 1.5A Mobile power bank. Data processing and analyses were performed using Python libraries: `NumPy` and `SciPy`.

3. Results

In this experiment, the frame rate was 30 Hz, but there were only six different frames per second gathered. It could be caused by large quantity of generated charge that could not be discharged by circuits in the image sensor. The dead time of this detector is 5 cycles, which corresponds to 1/6 s.

When an alpha particle interacts with the sensor, clusters of bright pixels in the image are formed due to the blooming effect. As shown in Figure 4, on the LCD the alpha particles were detected as white dots with diameters of about 5 to 7 pixels.

After an image is generated in the sensor, the SBC run a program from `OpenCV` library to read and processes the image. This program can classify the clusters and calculate parameters such as area, charge and image moment for bright pixels. We used the `cv.imread()` function to read and the `cv.imshow()` function to display the images.

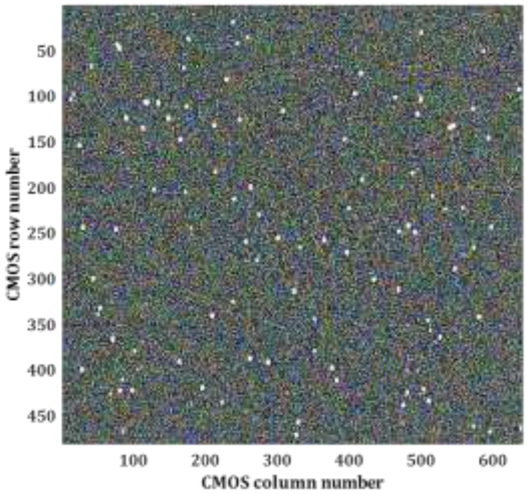

Fig. 4 Raw image captured with the modified webcam. Bright spots shows alpha particles hit on the CMOS image sensor

To further process the images, we converted the original color images to gray scale using the`cv2.cvtColor(image,cv2.COLOR_BGR2GRAY)` function of the `CV2` module and the resulting gray scale image is shown in Figure 5. Image blurring was achieved by convolving the image with a low-pass filter kernel. To remove small size clusters, image thresholding was carried out using `cv2.threshold()` function and the resulting binary image is shown in Figure 6. In this study, we intended to use the webcam at room temperature, therefore, several steps were taken to eliminate the thermal sensitivity of the image sensor. These include cleaning random dark noise off the images and discarding defective pixels. Of these noises, the latter leads to the Fixed Pattern Noise (FPN). Measurements of the values of these noises show that as the temperature changes from 20 to 40 °C the average values of these noises change slightly [25]. To obtain the average values of the dark and FPN noises, we blacked out the colour image sensor by aluminium layer deposition and recorded images without alpha particle irradiation. To minimize the impact of dark and FPN noises on the detection of ionizing particles, in the offline image processing, we subtracted the mean value of the noises from each image.

Figure 7 shows a histogram presenting data on pixel cluster sizes due to the interaction of α particles with CMOS image sensor. The histogram shows two peaks. The larger peak corresponds to 5.5 MeV α particle of ^{241}Am source. The small peak is due to background bright spots which can be eliminated by adjusting the thresholding algorithm parameters. The energy resolution of the CMOS sensor is rather poor, which is due to diffusion nature of the charge collected. The modified webcam has been tested successfully for standard ^{226}Ra alpha source.

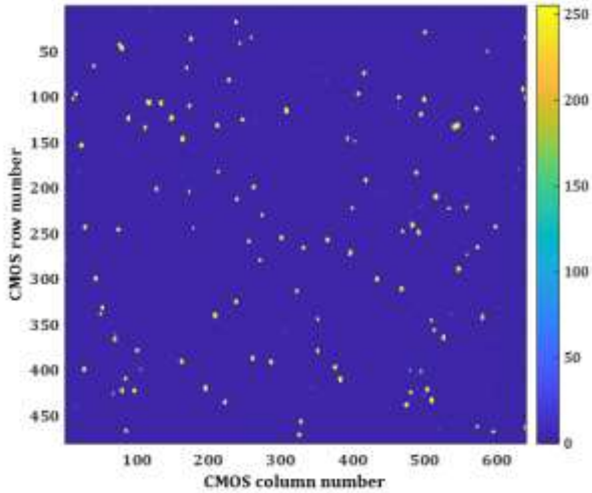

Fig. 5 Gray scale image as an input to thresholding algorithm.

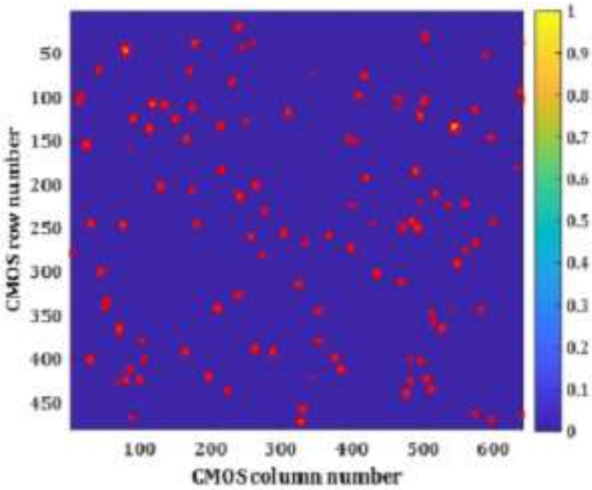

Fig. 6 Binary image as an input to cluster count algorithm.

A great interest in CMOS sensors in alpha particle detector applications exists because of their characteristics:

- Low cost and compact size make the CMOS sensor one of the best options for: environmental radon measurements and educational purpose in the laboratory course experiments.
- Spatial resolution: pixel size of 2.8 µm × 2.8 µm make theses sensors attractive for particle tracking in high energy particle physics, alpha particle scattering experiments and beam tuning in accelerators applications.

The CMOS detector has the ability to distinguish alpha particles with different energies. Alpha particles with energies deposit different amount of energy in the sensitive region of the CMOS. The higher the energy loss, the higher the number of created electron-hole pairs. Since the white spot size in Fig. 4 is proportional to the number of e-h pairs, by drawing a histogram of the spot radius one can distinguish alpha particles with different energies.

Fig. 7 pixel cluster sizes histogram for ^{241}Am alpha source. The peak of the distribution corresponds to the maximum energy of incident alpha particles (5485.56 keV).

An analytical function consisting of a Gaussian and a one-sided exponential function was proposed to describe the energy distribution of the detected alpha particles [27]. By fitting the analytical peak shape to the measured histogram, we performed energy calibration for the alpha particles emitted from ^{241}Am. The calibration parameters can be used to determine the alpha particle energy of an unknown source.

4. Conclusion

In this paper we have shown that the CMOS image Sensors can be modified and adopted for alpha particle detection and tracking purposes in Nuclear Physics experiments. A good spatial resolution (just few pixels in the immediate neighbourhood of the hit pixel) has been found for alpha particles. It was also demonstrated that, by proper energy calibration, the modified webcam can be used to measure the energy of alpha particles. The energy resolution of the CMOS sensor is rather poor, which is due to diffusion nature of the charge collected. Due to higher interaction probability of silicon, the CMOS detector has higher sensitivity than traditional gaseous Geiger tubes.

The detector is based on a low-cost CMOS image sensor and a low-cost Raspberry Pi SOC, which is powerful enough to process the information in real-time. It is highly portable and does not require high voltage supply and can be operated with a commercial mobile power bank. An image processing algorithm was developed using the OPENCV library, which was able to identify and extract the ionization events from the captured images. Its high sensitivity, spatial resolution, and temporal information for each event make the CMOS image sensor an attractive technology for α particle detection.

5. References

[1] Adachi, S., Tokuda, S. and Ishida, S., 1996. A CMOS detector readout front-end for X-ray digital radiography systems. IEEE Transactions on Nuclear Science, 43(1), pp.249-255.

[2] Lane, D.W., 2012. X-ray imaging and spectroscopy using low cost COTS CMOS sensors. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 284, pp.29-32.

[3] Castoldi, A., Guazzoni, C., Maffessanti, S., Montemurro, G.V. and Carraresi, L., 2015. Commercial CMOS image sensors as X-ray imagers and particle beam monitors. Journal of Instrumentation, 10(01), p.C01002.

[4] Castoldi, A., Guazzoni, C., Maffessanti, S., Montemurro, G.V. and Carraresi, L., 2015. Application of naked commercial CMOS sensors to X-ray fluorescence and X-ray beam monitoring. In 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) (pp. 1-3). IEEE.

[5] Haro, M.S., Bessia, F.A., Pérez, M., Blostein, J.J., Balmaceda, D.F., Berisso, M.G. and Lipovetzky, J., 2020. Soft X-rays spectroscopy with a commercial CMOS image sensor at room temperature. Radiation Physics and Chemistry, 167, p.108354.

[6] Cogliati, J.J., Derr, K.W. and Wharton, J., 2014. Using CMOS sensors in a cellphone for gamma detection and classification. arXiv preprint arXiv:1401.0766.

[7] Gumiela, Michał & Kozik, Rafał. (2012). Studies of the applicability of CMOS and CCD sensors for detection, dosimetry and imaging of alpha, beta, gamma, X-ray and proton beam spots.

[8] Faruqi, A.R., Henderson, R., Pryddetch, M., Allport, P. and Evans, A., 2005. Direct single electron detection with a CMOS detector for electron microscopy. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 546(1-2), pp.170-175.

[9] Foran, B., Barnett, J., Lysaght, P.S., Agustin, M.P. and Stemmer, S., 2005. Characterization of advanced gate stacks for Si CMOS by electron energy-loss spectroscopy in scanning transmission electron microscopy. Journal of electron spectroscopy and related phenomena, 143(2-3), pp.149-158.

[10] S. Kumar, R. Prakash, S. Chouhan and A. K. Salhan, "CMOS sensors for microscopy, spectrophotometry and as a transducer in biosensors," 2013 IEEE Point-of-Care Healthcare Technologies (PHT), 2013, pp. 196-199, doi: 10.1109/PHT.2013.6461318.

[11] Pallone, A. and Newton, N., 2011, March. WASTED at work: the Webcam Alpha Spectrometer Experiment Demonstrator. In APS Meeting Abstracts.

[12] Fryman, J. and Pallone, A., 2012, February. The WASTED Resolutions: exploration of the spatial and energy limits of the Webcam Alpha Spectrometer TEchnology Demonstrator. In APS March Meeting Abstracts.

[13] Griffin, R.H., Le, H., Jack, D.T., Kochermin, A. and Tarr, N.G., 2008, October. Radon Monitor using Custom α-detecting MOS IC. In SENSORS, 2008 IEEE (pp. 906-909). IEEE.

[14] Griffin, R.H., Le, H., Jack, D.T. and Tarr, N.G., 2008, October. αRAM: An α particle detecting MOS IC for radon monitoring. In 2008 1st Microsystems and Nanoelectronics Research Conference (pp. 73-76). IEEE.

[15] Gumiela, Michał. (2014). Hardware random numbers generator based on Am-241 alpha decay.

[16] Griffin, R.H. and Tarr, N.G., 2013, October. Optical image sensors and their application in radon detection. In Photonics North 2013 (Vol. 8915, p. 89151C). International Society for Optics and Photonics.

[17] Knoll, G.F., 2010. Radiation detection and measurement. John Wiley & Sons.

[18] Mendis, S., Kemeny, S.E. and Fossum, E.R., 1994. CMOS active pixel image sensor. IEEE transactions on Electron Devices, 41(3), pp.452-453.
[19] El Gamal, A. and Eltoukhy, H., 2005. CMOS image sensors. IEEE Circuits and Devices Magazine, 21(3), pp.6-20.
[20] Bigas, M., Cabruja, E., Forest, J. and Salvi, J., 2006. Review of CMOS image sensors. Microelectronics journal, 37(5), pp.433-451.
[21] Yadid-Pecht, O. and Etienne-Cummings, R. eds., 2007. CMOS imagers: from phototransduction to image processing. Springer Science & Business Media.
[22] Ohta, J., 2007. Smart CMOS image sensors and applications. CRC press.
[23] Kuroda, T., 2014. Essential principles of image sensors. CRC press.
[24] Belredon, X., David, J.P., Lewis, D., Beauchene, T., Pouget, V., Barde, S. and Magnan, P., 2002. Heavy ion-induced charge collection mechanisms in CMOS active pixel sensor. IEEE Transactions on Nuclear Science, 49(6), pp.2836-2843.
[25] Pérez, M., Lipovetzky, J., Haro, M.S., Sidelnik, I., Blostein, J.J., Bessia, F.A. and Berisso, M.G., 2016. Particle detection and classification using commercial off the shelf CMOS image sensors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 827, pp.171-180.
[26] PhysicsOpenlab @: http://physicsopenlab.org/2016/05/18/diy-webcam-particle-detector/
[27] L'Annunziata, M. F. (2012). Handbook of Radioactivity Analysis, Academic press. Waltham, USA.
[28] Auzinger, T., Habel, R., Musilek, A., Hainz, D., & Wimmer, M. (2012, August). GeigerCam: measuring radioactivity with webcams. In SIGGRAPH Posters (p. 40).