Gamma Radiation Sensing Using ZnO and SnO_2 Thick Film Interdigitated Capacitors

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***Abstract**: A novel cost-effective real-time gamma radiation monitoring system based on metal oxide thick films was designed and tested. The changes in capacitances of ZnO and SnO_2 thick film capacitors with interdigitated electrodes were monitored in real time under the influence of gamma radiation using miniaturized, low power, bi-directional wireless communication system. The capacitive interface circuitry was based on a Delta-sigma (ΣΔ) modulator using switched capacitor (SC) circuit architecture with integrated on-chip temperature sensor. At the base station side, an Frequency Shift Keying (FSK) receiver/transmitter is connected to another MCU unit, which send the received data or received instructions from a PC through a graphical user interface GUI. Industrial, Scientific and Medical (ISM) band RF (433 MHz) was used to achieve half duplex communication between the two sides. All the modules of the mixed signal system are integrated in a printed circuit board (PCB) of size 22.46x20.168mm. The overall system supply voltage is 2.7V maximum. ^{137}Cs source with an activity of 370 kBq was used. An increase in the values of capacitance with radiation was recorded for both films to a certain dose level, determined by the material of sensitive layer.*

1. Introduction

Adequate personal radiation dosimetry is highly essential in a wide range of areas, for example, medicine, industry, security and science. Unpredictable accidents could happen during transportation and storage of radioactive materials, such as nuclear waste and isotopes, and in industry, where radiation processing is used excessively. There is a growing need for compact, affordable, real-time active dosimeters, with a visual/audio alarm, if a critical threshold radiation dose is exceeded. A considerable engineers and material scientists efforts resulted in the development of low-power micro-systems for use in remote environmental or power plant monitoring [1].

The development of VLSI and silicon technology makes it possible to produce miniature highly integrated circuits with powerful functions. Also available are the chip-on-board techniques, which use bare dies bounded directly on the PCB substrate to decrease the overall dimension of the circuit board. Double-sided PCB technique could be efficient sometimes to produce very small modules with high efficiency and ease in implementation. These technologies allowed the development of miniature RF communication systems and accordingly various sensors monitoring devices.

Metal oxides and polymers are regarded as candidate materials for radiation sensing layers [2, 3, 4]. It is believed that ionising radiation causes structural defects (called colour centres or oxygen vacancies in oxides) leading to a change in their density on exposure to γ-rays. The advances in processing of metal oxides have contributed considerably to the development of novel affordable radiation detectors, which can be used for in situ measurements. Gamma rays produce a change in the density of charge carriers in semiconducting material, which alters the material properties in measurable way. This change provides information on the dose absorbed by the material. The effect of irradiating an electronic material and the consequent degradation in performance of devices made from such a material can follow a number of routes. The final result depends upon the type of radiation, its mode and rate of

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interaction with the materials, the type of materials, their particular contribution to the device function and the physical principles upon which the function of the device is based [5].

In this work, thick film technology was used, as it is known for its flexibility and cost-effective mass production [6]. ZnO and SnO_2 capacitors with Ag interdigitated electrodes were used as radiation-sensing layers. They were constantly exposed to γ-rays and the changes in the values of their capacitances were monitored. The compact wireless gamma radiation monitoring system along with corresponding circuit description is presented.

2. Experimental Procedure

2.1. Thick film sensors preparation

Radiation sensing devices were prepared by screen-printing onto alumina substrates using a DEK 1202 automatic screen-printer. The interdigitated structure was formed using Ag conductive pastes and had three fingers on each electrode. ZnO and SnO_2 were mixed with 7 wt.% of polyvinyl butyral (which acted as the binder) and a suitable amount of ethyleneglycolmonobutyalether to form insulative pastes. These were deposited over the interdigitated electrodes and dried at 120 °C for three hours to ensure complete evaporation of the solvent. The structure is shown in Fig. 1.

Interdigitated electrodes are advantageous as they allow one-sided access to the sensing layer [7]. Calculating the capacitance of these structures is complex and is normally achieved using a conformal mapping technique. The capacitance is largely dependant on the electrode gap (G), finger length (L) and width (W), the spatial wavelength ($\lambda = 2(W+G)$) and metallization ratio ($\eta = 2W/\lambda$) [8]. It can be seen that changes in the capacitances of ZnO and SnO_2 sensors will only occur when there is an alteration in the properties of the dielectric material deposited over the electrodes, as all other properties are fixed.

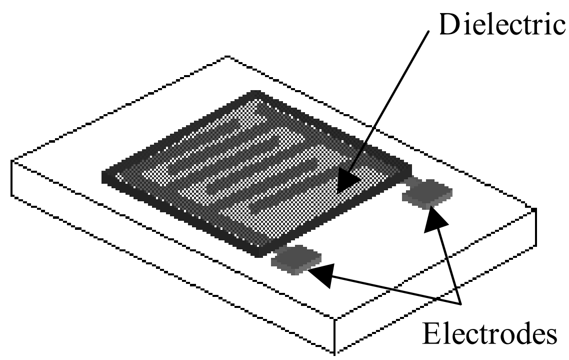

Fig.1. Structure of ZnO and SnO_2 sensors with interdigitated electrodes.

^{137}Cs (0.662 MeV) disk-type source with an activity of 370 kBq (provided by AEA Technology QSA GmbH as a standard reference gamma radiation source) was used to expose the samples to γ-radiation. The radioactive gamma-emitting element (3.18 mm x 5 mm) was encapsulated into a 2 mm thick high strength epoxy resin (diameter 25 mm) to shield any accompanying β-radiation. The source was held at a distance of 1 cm from the surface of the film at an angle of incidence of 0°.

The changes in the values of capacitance with radiation were measured wirelessly in real-time via the capacitive interface circuitry, described in the next section.

2.2. Circuit design

The capacitive interface circuitry is based on ΣΔ modulator using SC circuit architecture. The RF carrier frequency is in the 433 MHz ISM frequency band. GFSK modulation has been adopted in the design with a data rate of 100Kbps and frequency deviation ±50KHz. This modulation type results in a more bandwidth effective transmission-link compared with ordinary FSK modulation. Fig. 2 displays block diagram of the programmable transceiver module. The 8051-based MCU with its instruction code stored in 4KB RAM is supervising the system operation. When powered on, a bootstrapping program is activated and the MCU waits for code to be downloaded from the external serial EEPROM.

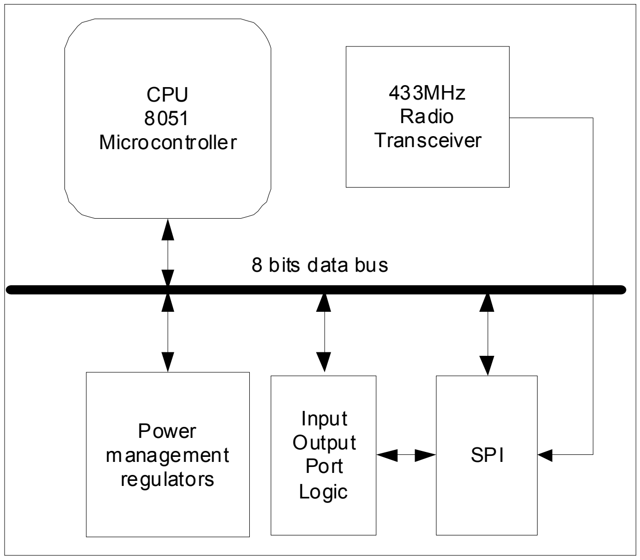

Fig.2. Block diagram of the programmable transceiver module

The transceiver part is accessed through an internal serial peripheral interface (SPI) unit. Mainly the RF transceiver consists of fully integrated frequency synthesizer, a power amplifier, and a modulator and receiver unit. Output power, frequency channels and other RF parameters are programmed by the use of on-chip SPI interface.

The power management unit is essential to regulate the power supplied to other parts of the module. Under program control, power management unit can turn on or off the RF transceiver and also provide the system with several low power modes.

The interface circuitry consisted of two stages as shown in Fig. 3. Three capacitors are connected to the first stage, sensor (Cs), reference (Cref) and feedback (Cfb) capacitors. When first switch (phi1) is on, the two capacitors will be charged to V+ and when (phi1) is off, the two capacitors are charged to V-. The output voltage represents the charge difference transferred from the first to second stage. The circuit proved to have a good performance and better immunity against drift and noise.

Capacitive sensors exhibit a change in capacitance in response to a change in physical stimulus. Most of the designed capacitive systems are based on converting the capacitance to voltage first. Then this voltage is converted into digital domain with high precision analog-to-digital converter (ADC).

ShockBurst™ protocol has been adopted with RF data transmission/receiving since it provides a high data rate. All high speed signal processing related to the RF protocol has been embedded in the transceiver part. By allowing the digital part of the module to run at low speed, while maximizing the data rate on the RF link, average current consumption can be much reduced.

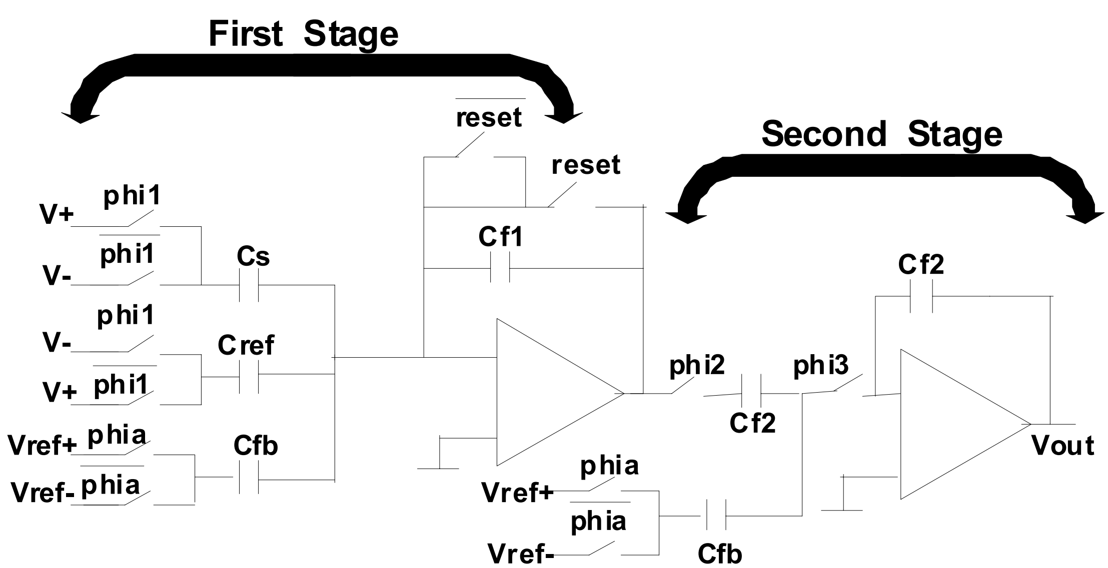

Fig. 3. Two stage ΣΔ modulator with sensor and reference connected to first stage.

The main functional blocks of the capacitive module are shown in Fig. 4. The system consists of on-chip temperature sensor, 24-bit SD modulator, digital filter, voltage regulator and serial interface – all integrated in one module. The module can operate with a single power supply of 2.7 V. The output information from the digital filter is read by the MCU through a serial interface part.

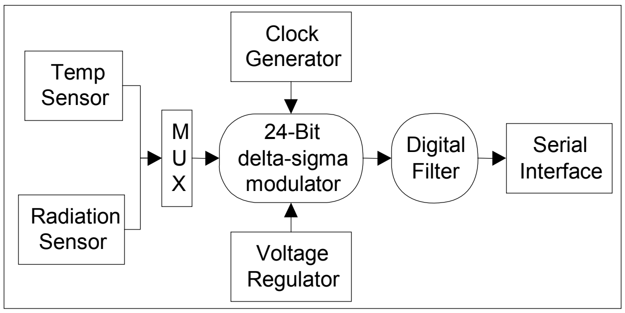

Fig.4. Block diagram of capacitive module

3. RESULTS AND DISCUSSION

3.1 ZnO sensor

Radiation-sensing properties of ZnO thick film doped with 0.1 wt.% of carbon were explored previously [9]. The changes in current-voltage characteristic of pn-junction structure on P⟨1 0 0⟩ Si wafer were measured under the influence of γ-rays. Carbon doping can increase the response of the material to gamma radiation, as more charge carriers are produced and the dose-response characteristic becomes more pronounced. A dose of 511 μSv caused a drastic increase in the values of leakage current in ZnO/Si diodes, e.g. the value of normalized current increased by 26 times.

In this work, ZnO thick film capacitors were studied. They exhibited a change the value of capacitance from 21.58 pF at a dose of 1 mGy to 28.33 pF at 2.3 mGy dose, as shown in Fig. 5A.

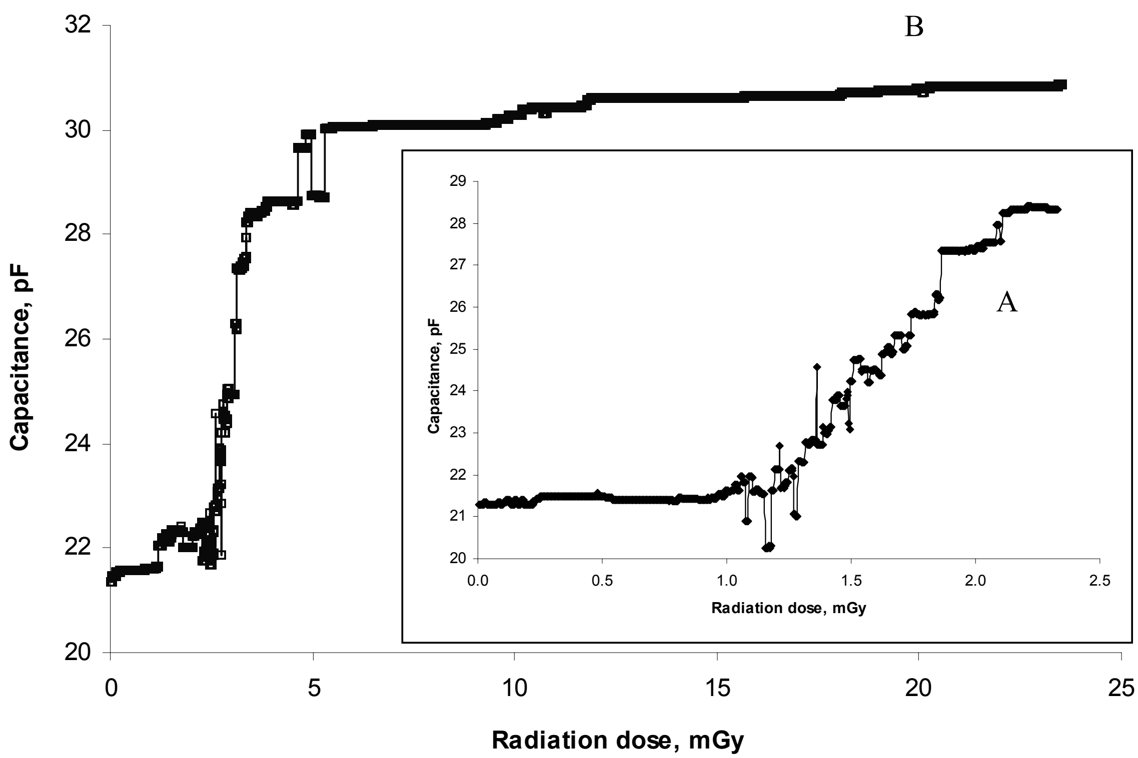

Fig. 5. Changes in the value of capacitance of ZnO thick films with radiation, where A) represents first-time measurement of ZnO sensor and B) shows the radiation response of previously irradiated and annealed sample.

At doses from 0 to 1 mGy little if any changes in the capacitance were recorded. This could be explained by co-existence of 2 processes, namely creation and annihilation of defects under the influence of radiation. After a dose of 1 mGy the creation of radiation-induced defects became more prevailing, which resulted an increase in capacitance.

To restore its initial electrical properties, previously irradiated ZnO sensor was annealed at 150 °C for 4 hours at a conventional oven. Afterwards, this sample was irradiated again and measurements were taken in a similar manner. Fig. 5B demonstrates very similar response of the annealed sensor to the one that was used first-time (please note difference in dose range scale). The repeatability of the results indicates the reusability of ZnO thick film capacitors, which is extremely important advantage for the design and development of cost-effective personal radiation monitoring systems.

To explore the response of ZnO sensor to higher gamma doses, a power supply was used to power the circuit. This allowed continuous monitoring of the capacitance value for few days, since very weak ^{137}Cs source was used due to safety precautions. Fig. 5B indicates that for dose range of 5 to 25 mGy no considerable changes were recorded. Based on these results, ZnO thick film capacitors with interdigitated electrodes can be recommended as reusable gamma radiation sensors in the dose range of 1 mGy to 2.5 mGy, where the value of 1 mGy is regarded as minimum detectable dose (MDD) or lowest limit of detection (LLD) [10].

3.2 SnO_2 sensor

Thick films of SnO_2 also showed an increase in the capacitance, but generally the behaviour of this sample was different to that of ZnO sensors. A considerable initial increase in the values of capacitance was monitored from 5.05 pF before irradiation to 8.69 pF at a dose 0.46 mGy (Fig. 6). Additional exposure to radiation up to a dose of 2.05 mGy caused no changes in the electrical properties of the SnO_2 thick films. However, subsequent irradiation with a dose of 3 mGy has lead to an increase in the capacitance value to the level of 12.62 pF.

Accordingly, SnO_2 sensors can be used for monitoring of radiation at lower dose range from 0 to 0.46 mGy, whereas after this dose the sensor response was not repeatable. This indicates radiation-induced damage to the properties of SnO_2 films, which were also restored by annealing.

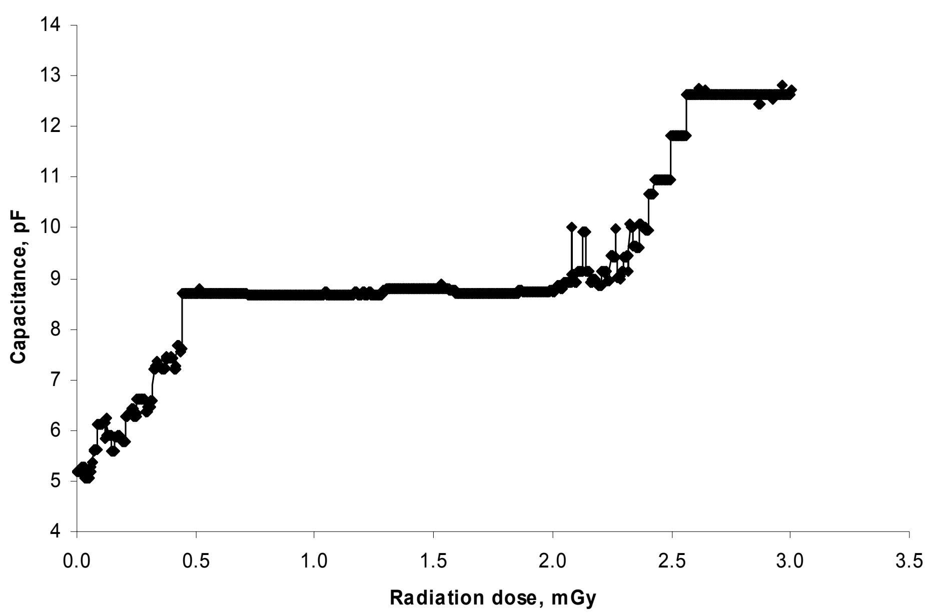

Fig. 6. Changes in the value of capacitance of SnO_2 thick films with radiation.

Combination of both ZnO and SnO_2 sensors into one radiation monitoring system (sensor array) gives the advantage of wider dose range coverage and better sensitivity over total working range [11].

CONCLUSION

The design of low power, miniaturized wireless module has been described. The module reads data from two sensors, temperature and radiation, and sends the information through a wireless link to a control station. The heart of the module is the transceiver, which contains an embedded MCU. All the operations of the transceiver part were controlled fully by software written into the MCU. The capacitive part is based on a high resolution ΣΔ ADC, which also provides high linearity. This part has been interfaced to the transceiver through a serial interface controlled by the MCU.

ZnO and SnO_2 thick film capacitors with interdigitated electrodes were used as gamma radiation sensors. Irradiation with doses from 1 mGy to 2.3 mGy caused the increase in the values of ZnO capacitor, whereas counterpart SnO_2 sensors were more sensitive to lower doses of radiation in the range of 0-0.46 mGy. Both sensors showed repeatable results after their properties were restored with annealing. The reusability of thick film sensors provides considerable advantage for designers of alternative cost-effective radiation monitoring system.

The proposed wireless real-time dosimetry system can be used in a wide range of applications, such as security tasks, environmental monitoring, nuclear waste control etc., where it is vital to minimize personnel exposure to radiation.

REFERENCES

[1] T. Akin, K. Najafi, and R. M. Bradley, "Wireless implantable multichannel digital neural recording system for a micromachined sieve electrode", *IEEE Journal of Solid-State Circuits*, vol. 33, pp. 109-118, 1998.

[2] A. P. Lima Pacheco, E. S. Araujo, and W. M. de Azevedo, "Polyaniline/poly acid acrylic thin film composites: a new gamma radiation detector", *Materials Characterization*, vol. 50, pp. 245-248, Mar. 2003.

[3] K. Arshak and O. Korostynska, "Preliminary studies of properties of oxide thin/thick films for gamma radiation dosimetry", *Materials Science and Engineering B*, vol. 107, pp. 224-232, Mar. 2004.

[4] K. Arshak, A. Arshak, S. Zleetni, and O. Korostynska, "Thin and thick films of metal oxides and metal phthalocyanines as gamma radiation dosimeters", *Nuclear Science, IEEE Transactions on*, vol. 51, pp. 2250-2255, 2004.

[5] A. G. Holmes-Siedle and L. Adams, *Handbook of radiation effects*. Oxford, New York, Oxford University Press, 1993.

[6] M. Prudenziati, *Handbook of sensors and actuators. Thick film sensors*. Amsterdam, Elsevier, 1994.

[7] A. V. Mamishev, K. Sundara-Rajan, F. Yang, Y. Du, and M. Zahn, "Interdigital sensors and transducers", *Proceedings of the IEEE*, vol. 92, pp. 808-844, 2004.

[8] R. Igreja and C. J. Rias, "Analytical evaluation of the interdigital electrodes capacitance for a multi-layered structure", *Sensors and Actuators, A: Physical*, vol. 112, pp. 291-301, 2004.

[9] K. Arshak, J. Corcoran, and O. Korostynska, "Gamma radiation sensing properties of TiO2, ZnO, CuO and CdO thick film pn-junctions", *Sensors and Actuators A: Physical*, vol. 123-124, pp. 194-198, Sept. 2005.

[10] K. Arshak and O. Korostynska, *Advanced Materials and Techniques for Radiation Dosimetry*. Boston, Artech House, 2006.

[11] K. Arshak and O. Korostynska, "Gamma radiation sensors arrays based on metal oxide thick films", *Sensor Review*, vol. 26, pp. 70-75, 2006.