Portable Real-Time Gamma Radiation Dosimetry System Using MgO and CeO\textsubscript{2} Thick Film Capacitors

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Abstract

In aggressive industrial processes and hard-to-reach places, in power plants and radioactive waste storage places it is extremely important to constantly monitor the level of radiation and to give an alert signal in case of emergency. The solution to this problem could be offered via portable real-time radiation monitoring system, in which case the risk of personnel exposure is minimised. We present such a system, where thick film MgO and CeO\textsubscript{2} capacitors with Ag interdigitated electrodes were used as prototype radiation sensors. A \textsuperscript{137}Cs \(\gamma\)-radiation source was used to test the system. Radiation changes the electrical properties of the material it penetrates. The degree of these changes provides information on the level of radiation received. Based on that, the capacitances of MgO and CeO\textsubscript{2} thick films were monitored during radiation exposure using a high precision capacitance to digital converter system. A monotonic increase in the values of capacitance from 1.493 pF to 1.537 pF was recorded for MgO as a result of 32.55 mGy \(\gamma\)-dose. Counterpart CeO\textsubscript{2} films were less susceptible to radiation, as the value of capacitance increased from 0.567 pF for non-irradiated sample to 0.583 pF when irradiated with the dose of 32.55 mGy. Moreover, the response of MgO sensor was monotonic over the whole range.

Keywords: \(\gamma\)-radiation, thick film, real-time dosimetry, circuit, interdigitated capacitor, assembly code

1 Introduction

Real-time radiation detectors have become an essential tool for emergency personnel who may have to respond to unknown accidents, incidents or terrorist attacks, which could involve radioactive material. Moreover, 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. Adequate real-time dosimetry is essential for the safe and acceptable use of radiation, radioactive materials and nuclear energy.

Considerable research into novel cost-effective sensors is underway, including efforts to enhance performance through both the materials properties and manufacturing technologies. Numerous efforts are devoted to investigating the influence of radiation on metal oxides and polymer materials, as a deep understanding of physical properties of these materials under the influence of \(\gamma\)-radiation is vital for the effective design of novel dosimeters [1].

Metal oxides were considered as suitable materials for gamma radiation sensing layers due to high sensitivity of their optical, electrical and structural properties to ionising radiation [1-4]. 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. 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 \(\gamma\)-rays [2, 4]. 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 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 [2].

In this work, thick film technology was used, as it is known for its flexibility and cost-effective mass production [5]. MgO and CeO\textsubscript{2} capacitors with Ag interdigitated electrodes were constantly exposed to gamma radiation and the changes in the values of their capacitances were monitored. The radiation monitoring system along with corresponding circuit and software description is presented.

2 Experimental Procedure

A DEK RS 1202 automatic screen printer was used for thick film fabrication. DuPont 4929 Ag conductive paste was used to deposit interdigitated electrodes. For the dielectric layers, polymer pastes were prepared using MgO and CeO\textsubscript{2} as the functional material. This was mixed with 7 wt.% of polyvinyl butyral (PVB), which acted as the binder. Finally, ethyleneglycolmonobutylerather was the solvent added to form a paste of suitable consistency.
Three layers of MgO paste were deposited over the electrodes and then fired at 120 °C for three hours to ensure complete evaporation of the solvent. The structure is shown in figure 1.

![Figure 1: Structure of MgO and CeO$_2$ interdigitated electrodes.](image)

Interdigitated electrodes are advantageous as they allow one-sided access to the sensing layer [6]. Calculating the capacitance of these structures is complex and 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 ($\eta = 2W/\lambda$) [7]. It can be seen that changes in sensor capacitance 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.

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

### 3 Results and Discussions

MgO is an insulator with a wide band gap, which is popular for use in a barrier material in electronic applications [8]. Undoped CeO$_2$ is an n-type material and its conductivity is directly related to oxygen diffusion. CeO$_2$ is an oxide with a fluorite structure, which has a property of deviating from stoichiometry as a function of temperature and/or pressure. Gamma radiation sensing properties of carbon-doped CeO$_2$ thick film resistors and diodes were explored [9]. Resistors doped with 0.2 wt.% of C showed gradual increase in the values of current with the increase in dose up to 4.42 mGy, whereas resistors with 0.5 wt.% of C sustained a lower dose of 1.7 mGy and were damaged on further exposure. PN-junctions formed with CeO$_2$ films, printed on single side polished P(100) Silicon wafers, exhibited the most sensitivity to gamma radiation. They showed significant increase in the values of leakage current with the increase in dose up to 0.57 mGy and are therefore suitable for low-dose dosimetry applications [9].

To examine the morphology of the samples prepared in this study, Scanning Electron Microscopy (SEM) of the MgO and CeO$_2$ thick film layers was conducted using a Joel JSM-840 SEM at a magnification of 10000. For MgO, the image revealed a rough and varied film surface as shown in figure 2. The particle size ranges from less than 0.5 µm to 1 µm in diameter.

![Figure 2: SEM of the MgO thick film at magnification of 10000.](image)

Figure 3 shows the CeO$_2$ film. It appears to consist of flake like particles with an average size of 5 µm.

![Figure 3: SEM of the CeO$_2$ thick film at magnification of 2000.](image)

Figure 4 shows the change in the value of capacitance with radiation dose for MgO thick film capacitor with interdigitated electrodes. A monotonic increase in the values of capacitance from 1.493 pF to 1.537 pF was recorded as a result of 32.55 mGy $\gamma$-dose. Figure 5 shows the change in the value of capacitance with radiation dose for counterpart CeO$_2$ samples. They were less susceptible to gamma radiation, as the value of capacitance increased from 0.567 pF for non-irradiated sample to 0.583 pF for irradiated with the
dose of a 32.55 mGy. Moreover, the response of MgO sensor was monotonic over the whole range, which is preferable for dosimetry applications.

Figure 4: Change in the value of capacitance with radiation dose for MgO thick film capacitor.

Figure 5: Change in the value of capacitance with radiation dose for CeO₂ thick film capacitor.

4 Circuit

The circuit design required a system capable of measuring capacitances changes with high precision. For this the AD7746 24-bit capacitance to digital converter was chosen for its inherent high-resolution architecture. The AD7746 allows 19-bit effective resolution at a 16.6 Hz data rate, high linearity (±0.01%) and high accuracy (±2 fF factory calibrated). The AD7746 capacitance input range is ±4 pF (changing), while it can accept up to 17 pF absolute capacitance (not changing), which is compensated by an on-chip digital to capacitance converter (CAPDAC).

In order to control the AD7746 a suitable processor was required. The ADuC831 was chosen and interfaced to the AD7746 by use of the I²C bus. The AD7746 can be fully controlled from the I²C bus and also allows multiple AD7746 to be connected simultaneously. Figure 6 shows a block diagram of the AD7746.

In Figure 7 a block diagram of the ADuC831 microprocessor is presented. The only functionality required from this tightly packed IC was that of the I²C bus, interrupt line input port p3.2 and an output port p3.4 to show that the system is functional. Although this processor probably exceeds the requirements of this application, its ease of use with regards to I²C routines and RS232 programming made it a suitable candidate for the initial test system.

Notice the use of the ADP3303 regulated power supply, as shown in figure 8. The system can run on a direct 5v or 3v volt supply. However, to keep power consumption to a minimum this above approach was chosen as it reduces noise in the capacitance circuit.
The ADM202 simply converts the UART signals from the ADuC831 to the proper voltage levels, TTL to Inverted CMOS, so that the system can be interfaced to a PC. The full schematic for the prototype system can be seen in figure 9.

5 Software

Some initial assembly code had to be written and downloaded to the ADuC831 internal EEPROM. This allowed for the system to be fully controllable with regards to time and resolution from the host based PC system. A second piece of software was designed to make the control of the system easy whilst displaying the results in a scientific manner. To keep the software description as simple as possible, the internal workings of the ADuC831 with regards to I2C bus or Serial port Communication is not discussed as several references/code samples can be found on the Analog web site [10, 11].

5.1 Assembly code

The code begins by setting the parameters for the serial port baud settings (9600, 8, n, 1) and initialising the I2C bus. The system interrupts are then set to be edge triggered and enabled. The parameters for the slave address and the configuration mode are stored. The I2C bus register is set so that the ADuC831 is in master mode, the SDATA and SCLOCK lines are high and the status bits are cleared.

A loop then begins, figure 10, which awaits the ASCII character 1 or 2 in the serial port buffer. If the number 1 or 2 is not received the loop jumps back to start else if its 1 it starts the gathering capacitance value routine by first acquiring the slave device (AD7746) on the I2C bus, setting it to single conversion mode with capacitor inputs on the C+ and C- terminals, at a rate of 16 Hz (best noise performance [11]). The AD7746 then takes a capacitance reading and sets its ready signal low. The 24-bit capacitance value is then stored internally on the AD7746 in registers 0x01, 0x02 and 0x03. On the ready signal going low an interrupt is generated causing the ADuC831 to flash the LED connected to pin 3.4. It then acquires the I2C bus and accesses the capacitor storage registers. The values are then stored internally in the ADuC831’s ram before being converted to ASCII code and transmitted through the UART to the host PC system. If the ASCII character 2 is received the ADuC831 again acquires the I2C bus and sends the IDLE mode value to the configuration register of
the AD7746. The assembly code was compiled using the ASM51 assembler and downloaded using the serial programmer port of the ADuC831.

...board tracks. The user then sets the time base in milliseconds between samples and presses the go button.

Figure 11: LabView user program for control of system and display of results.

The flow diagram, shown in figure 12, displays the methodology behind the LabView. The programs layout is illustrated in figure 13 so that the inner workings of the LabView code can be seen.

Figure 12: Graphical Representation of LabView program
6 Conclusions

In this work, the radiation induced changes in the capacitance of MgO and CeO$_2$ films were investigated using a high precision capacitance to digital converter system. An increase in capacitance was observed for both materials. In the case of MgO, the capacitance changed from 1.193 pF to 1.537 pF for a 35.55 mGy $\gamma$-dose. For CeO$_2$ the capacitance increased from 0.567 pF to 0.583 pF, for the same dose.

It can be seen that the system outlined above, provides a user-friendly method of collecting data from the radiation sensor under test and creating viewable charts on a PC based system. This portable real-time dosimetry system can be used in a wide range of applications, such as security tasks, environmental monitoring, nuclear waste control etc., where personnel exposure to radiation can be minimised.

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8 References


