Optimization of Flexible Ag-Chalcogenide Glass Sensors for Radiation Detection

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Abstract— We demonstrate how the radiation response and performance of Ag-chalcogenide glass radiation sensors fabricated on a flexible substrate can be optimized by modifications of spacing between electrodes.

Index Terms— chalcogenide glass (ChG), dosimetry, dynamic range, flexible radiation sensor

I. INTRODUCTION

In this paper we investigate the impact design variables have on the performance of a novel flexible total ionizing dose (TID) detector technology. The sensors are made by depositing silver electrodes on top of a thin chalcogenide glass (ChG) film. Before exposure to ionizing radiation, the devices exhibit very high electrical resistance (~10¹² Ω) between the adjacent surface electrodes. When exposed to ionizing radiation (e.g., gamma rays), silver ions from the electrodes start to migrate into the chalcogenide glass film.

Buildup of Ag in the ChG glass results in significant decrease in film resistivity (~10³ Ω), (Fig. 1) [1]-[12]. This interesting property made Ag-ChG based devices ideal for diverse applications. A few notable examples are: manufacturing of relief images in optical elements, micro photolithographic structures, direct imaging by photoinduced silver into chalcogenide glass and non-volatile memory technologies [8] [13]. Also, considerable amount of research have been done lately to investigate the impact of total ionizing dose on the electrical characteristics of devices made of Ag-ChG [14] [15]. This was done to investigate their suitability for use in an ionizing radiation environment. The change of resistance while exposed to ionizing radiation suggests the potential use of flexible Ag-ChG sensors in radiation detection applications that requires attachment to non-flat objects such as flasks, barrels, and pipes. Fig. 2 shows an array of Ag-ChG flexible sensor attached around a pipe.

Fig. 1. Typical “evolution of resistance” plot of the Ag-ChG flexible sensor devices in response to increasing ionizing dose level. Geometry of these sensor devices such as spacing shows significant influence on determining the dynamic range (DR) and the limit of detection (LOD). Image © IEEE [1].

Fig. 2. Manufactured samples bent around a 2.58 inch diameter pipe.

Since structural features likely control the radiation response characteristics of these sensors, identification of these features would enable optimization of the sensor for specific uses. From our experiments, we have determined that these features include: 1) chalcogenide glass film composition

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and thickness; 2) electrode size and placement. The impact of film processing on sensor performance has been investigated in previous works [3], [5], [16]-[17]. In this paper, the impact of spacing between electrodes on sensor characteristics, is investigated to understand the role electrode design has on the limit of detection (LOD) and dynamic range (DR) of the detector. The term LOD indicates the dose level where the undoped/high resistance state (HRS) starts to decrease linearly in response to increased dose level and dynamic range (DR) is the ratio of resistance level between undoped/HRS and doped/low resistance state (LRS) (Fig. 1). In the next section, we describe how the devices are manufactured along with experimental methods. Subsequently, in the results and discussion section, we present the research findings.

II. DEVICE FABRICATION AND TEST PROTOCOL

![Fabrication Process Steps](image)

The sensor devices were manufactured on a 125 µm thick flexible polyethylene naphthalate (PEN) substrate. This lightweight and cheap polymer substrate can reduce the cost of manufacturing process as well as being compatible for roll-to-roll deposition processes [18]. The manufacturing process begins with room temperature blanket deposition of 10 nm Ge_{20}Se_{80} on a flexible substrate at a rate of 0.01 nm/s using a Cressington 308 evaporator (Fig. 3). Next, instead of using standard photolithography technique, a shadow mask is placed on top of the deposited film to form Ag surface electrodes. This was done to avoid chance of interaction between photolithography chemicals and the deposited germanium selenide film. The mask was designed to make an array of 2 mm diameter electrodes with variable spacing (2 mm, 4 mm, 6 mm, 8 mm and 10 mm) between nearest electrodes (Fig. 4).

Using the same deposition tool, 35 nm thick Ag electrodes are deposited at 0.1 nm/s rate at room temperature. These electrodes are used as contact pads for the quasi static DC electrical measurement as well as the source of Ag⁺ ions that transport into Ge_{20}Se_{80} chalcogenide film when exposed to ionizing radiation.

![Cross-section View](image)

Fig. 4. Cross-section view of the manufactured samples with fixed electrode diameter of 2 mm and variable spacing of 2 mm, 4 mm, 6 mm, 8 mm and 10 mm (8mm and 10mm not shown)

![Optical Illustration](image)

Fig. 5. Optical illustration shows lateral dissolution of Ag into Ge_{20}Se_{80} chalcogenide films in response to increasing dose level. The electrode diameter of this particular test sample is 6 mm and the spacing (l) between them is 3 mm. (a) shows the pre-exposure state of the samples. The remaining images show the radiation induced doping process of Ag: (b) after 1.31 Mrad(Ge_{20}Se_{80}), (c) after 2.55 Mrad(Ge_{20}Se_{80}), and (d) after 4.56 Mrad(Ge_{20}Se_{80}). ‘l’ is the spacing between two electrodes, ‘w’ is the width/spread of the doped region that increased with dose level.
Both the control and exposed devices were manufactured at the same time to reduce variability. After fabrication, an initial pre-irradiation electrical resistance measurement was done on both control and exposure samples. Then, exposure samples were placed into a Gammasell 220 for $^{60}$Co gamma-ray exposure at a dose rate of 477.5 rad(Ge$_{20}$Se$_{80}$)/min. They were periodically unloaded from the Gammasell chamber for a short amount of time to measure the electrical resistance between nearest electrodes using a semiconductor parameter analyzer (Agilent 4156C). The same measurements were performed on unexposed control samples. To avoid redox reaction at the electrodes, a very small bias voltage (10 mV) has been used to sample the resistance level. Optical images were taken after each measurement step to visually monitor the transport of Ag from the surface electrodes into Ge$_{20}$Se$_{80}$ film at increasing dose levels (Fig. 5). The $^{60}$Co gamma ray exposure continued up to a maximum dose level of 4.5 Mrad(Ge$_{20}$Se$_{80}$). During exposure, all the test samples were left floating by keeping the electrodes unconnected. Fig. 6 shows optical images of the control and test samples (fixed electrode diameter, variable spacing) after 4.5 Mrad(Ge$_{20}$Se$_{80}$).

III. RESULTS AND DISCUSSION

Fig. 7 shows the evolution of resistance with increasing dose level when the electrode area is fixed and the spacing between adjacent electrodes is varied. After the maximum dose level of 4.5 Mrad(Ge$_{20}$Se$_{80}$), out of five arrays of electrodes with different spacing, the intermediate ChG region of only two arrays with minimum spacing (2 mm and 4 mm) were completely doped by Ag from surface electrodes (see Fig. 6(b)).

From Fig. 7, we can see that the limit of detection (LOD) for a 2 mm spaced array is much lower compared to the array with 4 mm spacing. Both Figs. 6(b) and 7 shows that even after the maximum dose level of 4.5 Mrad(Ge$_{20}$Se$_{80}$), arrays with higher spacing (6 mm, 8 mm and 10 mm), did not reach full doping saturation. This indicates that the LOD of this Ag-ChG sensor devices can be optimized by adjusting the spacing between nearest electrodes. Apart from that, dynamic range (DR), which is a ratio between high resistance state (HRS) and low resistance state (LRS), can also be controlled by changing the spacing. The doped resistance or LRS between two nearest electrodes can be computed as:

$$R_{LRS} = \frac{\rho l}{wt}$$

Where $\rho$ is the resistivity of the Ag-Ge-Se ternary, which depends on the atomic fraction ($x$) of Ag present in Ag$_x$Ge$_y$Se$_z$, $l$ is the spacing between two electrodes, $w$ is the width/spread of the doped region (Fig. 5(c), 5(d)) and $t$ is the thickness of ChG film [17]. Fig. 7 shows that by reducing spacing ($l$) between the nearest electrodes, DR can be increased (as LRS reduces when $l$ decreases). The dependence of LOD and DR on electrode spacing show the importance of this particular design parameter to obtain desired performance characteristics of this radiation sensor.

IV. CONCLUSION

In this work, we have reported test results on Ag-ChG flexible radiation sensors with different electrode spacing. The
results show that by changing the spacing between Ag electrodes, it is possible to change the dynamic range of obtained resistance then to tune the detection range. In addition, the limit of detection can also be changed to a desired dose level by changing this parameter. This easily implemented design modification enable sensor designers to optimize sensors for intended applications.

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