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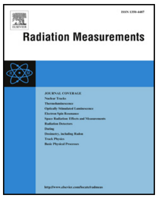

Preliminary characterization of the response of an organic field effect transistor to ionizing radiation

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ABSTRACT

Organic thin film transistors (OTFT) were investigated as a novel radiation detector. The OTFTs were fabricated on a flexible PET substrate with a PMMA dielectric layer and a pentacene semiconductor. OTFTs were irradiated up to 400 Gy using kilovoltage (100 and 180 kVp) and megavoltage (6 and 18 MV) photon beams. One OTFT was irradiated to 1000 Gy using 6 MV to observe the longevity of the device. Irradiating the devices caused a positive threshold voltage shift in each device. The magnitude of the threshold voltage shift per unit dose decreased with accumulated dose until it stabilized after approximately 200 Gy. The sensitivity ranged from 2 to 10 mV/Gy at low accumulated dose and decreased to 0.5–1.5 mV/Gy after 200 Gy of accumulated dose across the various OTFTs. After 400 Gy all of the devices were still functional with a loss in mobility of about 15, 14, 12 and 9% for beam qualities of 100 kV, 180 kV, 6 MV, and 18 MV, respectively. After 1000 Gy using 6 MV the OTFT was still functional with a sensitivity of 0.8 ± 0.1 mV/Gy after 300 Gy. This study showed that an OTFT on a flexible substrate shows a measureable response to photon irradiation of various qualities.

1. Introduction

Exposing electronics to ionizing irradiation has a number of consequences which include charge buildup in the dielectric, leading to an alteration of device performance. By calibrating the rate of change of a particular metric (e.g. threshold voltage shift in MOSFETs) as a function of absorbed dose, these devices can be used as dosimeters. Conventional silicon-based devices (e.g. diodes, MOSFETs, etc.) have been studied and used clinically for radiation sensing applications for decades (Hughes, 1973; Jornet et al., 2004; Rosenfeld, 2002; Scalchi and Francescon, 1998) and now organic electronics are of interest.

The trapping of charge in the dielectric of a MOSFET results in changes in device properties, notably a shift in the threshold voltage (Oldham and McLean, 2003; Schwank et al., 2008). The shift in threshold voltage is approximately linear over a range of accumulated dose allowing for a MOSFET to be used as a dosimeter (Ramaseshan et al., 2004). Beyer et al. (2008) measured the useful lifetime of a MOSFET to be 80 Gy, but the lifetime can vary depending on the sensitivity and fabrication of the device. For therapy photon beams (Co-60 to 18 MV) several studies have found an energy dependence of less than 3% (Beyer et al., 2008; Halvorsen, 2005; Ramaseshan et al., 2004). However, another study found about a 12% reduction in response when comparing 18 MV to Co-60 (Panettieri et al., 2006). MOSFET energy dependence strongly depends on the fabrication process and therefore each device should be calibrated for the energy and modality in which it is to be used. At diagnostic energies MOSFETs can have an over response of more than 4 times that of therapeutic beams (Edwards et al., 1997; Wang et al., 2005). The commercially available microMOSFETs show no measureable directional, dose rate, or temperature dependence (within the ± 2% reproducibility of the detector) (Ramaseshan et al., 2004).

The response to irradiation of organic semiconductors in diodes has been investigated with photon energies of 17.5 keV and 6 MV (Intaniwet et al., 2011; Mills et al., 2013). In both cases the induced photocurrent was proportional to the incident dose rate, showing potential to be a radiation detector. Several studies have investigated the response of an organic thin film transistor (OTFT) with irradiation and showed a degradation of the mobility with dose. Raval et al. (2009) irradiated an OTFT with a P3HT semiconductor on a silicon dioxide insulating layer with Co-60 up to 41 krad. They determined that the mobility of the device decreased, the off current increased, and the on current decreased with increasing dose. Furthermore, they observed a negative shift in the threshold voltage attributed to positive charge accumulation in the SiO_2. Kim et al. (2016) investigated the effects of

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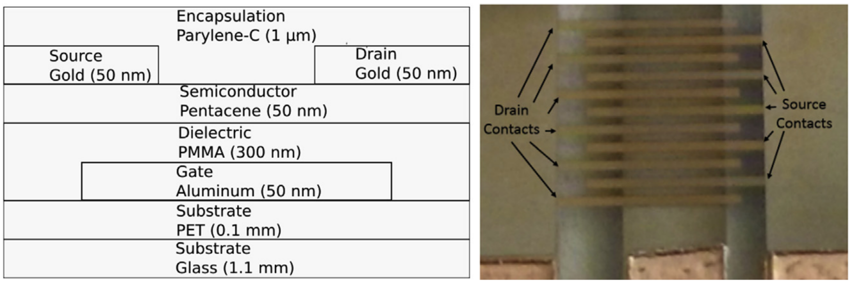

Fig. 1. Illustration of the OTFT design used in this study. On the left is a schematic diagram showing the material compositions and thicknesses of the layers of the OFTF. On the right is a top-down photograph of the OTFT.

electron beam irradiation on a rubrene semiconductor OTFT. They irradiated a Si/SiO$_2$ substrate before deposition of rubrene and another after deposition of rubrene to differentiate signal change due to irradiation of the insulator and semiconductor. When the Si/SiO$_2$ substrates were irradiated before the deposition of rubrene the mobility fell by less than 50% after 10^7 rad. Irradiating the OTFT after the deposition of rubrene caused the mobility to decrease by more than 50% after 10^5 rad and no charge transportation was observed after 10^7 rad. They concluded electron irradiation to the organic semiconductor was the dominant factor of degradation of the OTFT.

An OTFT is a voltage controlled current source whereby the bias applied to the gate electrode controls the current flow through a thin organic semiconducting layer (Fig. 1). The semiconductor is separated from the gate electrode by a thin dielectric layer. Applying a bias on the gate electrode causes a buildup of mobile charge in the semiconductor, close to the semiconductor/dielectric interface which balances the charge applied to the gate. Applying a bias between the source and drain electrodes, which are directly attached to the semiconductor, allows current to flow through the transistor. The gate bias controls the charge density in the semiconductor and therefore the amount of current that can flow between the source and drain. Like MOSFETs, OTFTs control the flow of current by adjusting the gate bias, but unlike MOSFETs, OTFTs can be made entirely using solution processing techniques such as inkjet printing, spin coating, and screen printing allowing large area fabrication at low cost (Arias et al., 2010). This, along with the use of flexible plastic substrates could allow easy fabrication of point detectors, 2-dimensional arrays, and flexible in-vivo dosimetry systems.

In this study OTFTs were made on a flexible substrate that was mounted on a glass slide. The change in threshold voltage and mobility of the OTFTs were measured as a function of dose. The sensitivity, lifetime, and energy dependence of the OTFTs were measured using various photon beam qualities.

2. Methods

2.1. OTFT fabrication

Fabrication of OTFTs followed established methods from the literature (Dimitrakopoulos et al 1996, 1999). Briefly, a 125 µm polyethylene terephthalate (PET) film (Tekra, New Berlin, USA) was mounted on a glass slide to allow spin coating and better alignment during subsequent vapor deposition steps. PDMS was made by mixing Sylgard 184A and B (Dow Corning Corporation, Midland, USA) in a 10:1 ratio (polymer to curing agent), spin coated onto the glass at 2000 rpm for 1 min, and cured for 30 min at 150 °C to facilitate smooth adhesion of the PET. A 50 nm aluminum gate was deposited with thermal evaporation at a rate ~1 Å/s. A 6.0% by weight solution of PMMA (Sigma-Aldrich, St. Louis, USA) in toluene was spin coated for 60 s at 1000 rpm. The films were heated at 70 °C for 2 h to evaporate residual toluene leaving a dielectric layer of PMMA. A 50 nm pentacene (TCI America, Portland, USA) layer was deposited with thermal evaporation at a rate ~1 Å/s with the substrate held at 50 °C during evaporation. Gold source and drain electrodes were thermally evaporated at a rate of ~1 Å/s to a thickness of 50 nm. The device was encapsulated with ~1 µm of parylene-C. As illustrated in Fig. 1, the source-drain electrodes were configured in an interdigitated configuration with at W:L ratio of 125. Copper tape was attached to the gold electrodes to permit easy connection of cabling.

2.2. OTFT irradiation setup

OTFTs were irradiated with both an Xstrahl 300 orthovoltage x-ray unit (Xstrahl Ltd., Surrey, UK) (100 and 180 kVp) and a Varian Clinac 21EX (Varian Medical Systems, Inc., Palo Alto, USA) medical linear accelerator (6 and 18 MV photons) (seeFig. 2). For the orthovoltage irradiations, OTFTs were placed on top of a 15 cm stack of Solid Water (Sun Nuclear Corp., Melbourne, USA). A 5 cm diameter, 30 cm length cone was used to deliver dose to the device. For the megavoltage irradiations, the OTFTs were positioned on top of a 10 cm stack of Solid Water and below an additional 5 cm of Solid Water. To prevent the build up material from damaging the OTFTs, 3 mm shims of PMMA were used to maintain a small air gap between the top of the OTFT and the bottom of the Solid Water. All machine outputs were measured with a calibrated ionization chamber.

During irradiations a dual channel SMU (Keithley 2614B, Tektronix, Inc., Beaverton, USA) was used to apply a +10 V bias across the OTFT dielectric (source and drain contacts were shorted to ground potential). The SMU was also used to measure transfer curves prior to any exposure ($n = 5$) and then following each exposure. Transfer curves were measured with the drain/source bias held at −50 V and the gate/source voltage swept from 10 V to −50 V in 1 V increments, with an integration time of 0.3 s per data point. To extract the mobility and threshold voltage the square root of the drain current was plotted as a function of the gate bias with the drain held at −50 V (Fig. 3). The threshold voltage is given by the x-intercept of the fit to the linear portion of the curve (i.e. above threshold) and the mobility can be calculated from its slope using the equation:

$$Slope = \sqrt{\frac{\mu W C_{ox}}{2L}} \tag{1}$$

Where µ is the mobility, C_{ox} is the dielectric capacitance per unit area (i.e. capacitance of the PMMA), and W and L are the width and length of the channel of the OTFT. The value of C_{ox} was directly measured using a PMMA film capacitor fabricated using the same conditions as the OTFT dielectric. Curves were measured at 10 Gy and 20 Gy intervals for the kilovoltage and megavoltage photon beams, respectively. All measurements were performed at room temperature in a climate-controlled environment that ensured stability during measurements.