Radiation Physics and Chemistry 85 (2013) 102–106

Contents lists available at SciVerse ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

A comparative study of X-ray shielding capability in ion-implanted acrylic and glass

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HIGHLIGHTS

► Synthesis of ion-implanted acrylic and glass for X-ray attenuation.
► X-ray attenuation of implanted samples increase with dose of ions.
► Implanted glass has the best X-ray attenuation property.
► A higher dose through prolonged time is necessary for implanted acrylic.

ARTICLE INFO

Article history:
Received 22 November 2012
Accepted 22 December 2012
Available online 31 December 2012

Keywords:
Sample matrix
Nominal dose
RBS ion concentration
Depth profile
Implanted ions
X-ray linear attenuation coefficient

ABSTRACT

Samples of acrylic and glass were implanted with tungsten (W) and lead (Pb) to investigate their X-ray attenuation characteristics. The near-surface composition depth profiles of ion-implanted acrylic and glass samples were studied using ion-beam analysis (Rutherford backscattering spectroscopy—RBS). The effect of implanted ions on the X-ray attenuation ability was studied using a conventional laboratory X-ray machine with X-ray tube voltages ranging from 40 to 100 kV at constant exposure 10 mAs. The results were compared with previous work on ion-implanted epoxy. As predicted, the RBS results and X-ray attenuation for both ion-implanted acrylic and glass increase with the type of implanted ions when compared to the controls. However, since the glass is denser than epoxy or acrylic, it has provided the higher X-ray attenuation property and higher RBS ion concentration implanted with a shorter range of the ion depth profile when compared to epoxy and acrylic. A prolonged time is necessary for implanting acrylic with a very high nominal dose to minimize a high possibility of acrylic to melt during the process.

1. Introduction

Hitherto, the application of ion implantation has become increasingly used due to the capability of accurate control on the number of implanted ions and the implanted depth distribution profile. This enables scientists to further improve the X-ray absorption capacity of shielding materials such as glass and polymers (Anders, 1997; Chen et al., 2001; Dworecki et al., 2004; Evans et al., 1995; Hubler, 1981; Kozlov et al., 2002; Lee et al., 1993; Lopatin et al., 1998; Soares et al., 2004; Wu et al., 2000; Yuguang et al., 2000). For example, a recent research by Rodríguez et al. (2007) has shown that ion implantation is an effective technology for implanting elements into polymers for surface modification to improve their mechanical properties such as hardness and elastic modulus. In addition, promising material comprising Cu nanoparticles in a ZnO matrix for exhibiting the phenomenon of self-defocusing and possessing a high nonlinear absorption coefficient for the usage as an active light intensity limiter in the visible spectral range was successfully obtained by the ion implantation technique by Stepanov et al. (2004). Furthermore, our previous work on epoxy implanted with lead, tungsten and gold ions showed a higher X-ray attenuation of when compared to pure epoxy (Noor Azman et al., 2012).

Glass is one example of materials used in shielding of ionizing radiations, especially for X-rays and gamma-rays, but it is heavy, expensive and very brittle. So, it is not surprising that the application of polymers in X-ray shielding technology is increasing steadily. This is due to a number of advantages that glass could not meet because of their unique properties, such as low manufacturing cost and rugged shatter-resistant material (Dworecki et al., 2004; Soares et al., 2004). But due to its high density as compared to polymer, glass

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http://dx.doi.org/10.1016/j.radphyschem.2012.12.021

is still in use for ionizing radiation shielding purposes since it can provide higher attenuation than polymer of the same thickness (Chanthima et al., 2011).

The aim of the present work was to synthesize, characterize and compare the X-ray attenuation properties and near-surface composition profiles of acrylic and glass implanted with tungsten and lead for X-ray shielding purposes. These results were also compared with our previous work done on ion-implanted epoxy (Noor Azman et al., 2012).

2. Materials and methods

The works of ion-implantation and the ion beam analysis by Rutherford backscattering spectroscopy (RBS) was conducted at Australian Nuclear Science and Technology Organization. As a continuation of our study to improve the X-ray shielding materials, we used here as base materials a commercial acrylic and a commercial glass. Both these materials were implanted with tungsten and lead. For reasons of comparing all different materials, we used the same nominal doses that were used in our previous work on ion-implanted epoxy, which for tungsten (W) was (7×10^{14} ions/cm^2) and for lead (Pb) was between (7×10^{14} ions/cm^2) and (1.4×10^{15} ions/cm^2) in order to prevent possible melting and/or decomposition of the polymer sample matrix during implantation. The ions were produced by a metal evaporation and a direct extraction ion source. The charge distribution of positive ions of W and Pb as measured previously by RBS are: $W^{+1}=1\%$, $W^{+2}=16\%$, $W^{+3}=58\%$, $W^{+4}=25\%$, and $Pb^{+1}=35\%$, $Pb^{+2}=64\%$, $Pb^{+3}=1\%$ which are nearly the same as the theoretical prediction by the Debye–Huckel approximation of non-ideal plasma (Anders, 1997). The RBS measured values of the charge distribution provided an average charge of $W^{+3.07}$ and $Pb^{+1.66}$ With these values and the nominal acceleration voltage of 40 kV used in this study, an average implantation energy of W=122.8 keV and Pb=66.4 keV was afforded to the ions prior to implantation. The beam size was close to 20 cm^2, and the beam current used in this experiment was around 30 μA. The ion fluence was monitored by converting the ion target current into pulses using a current-to-frequency convertor.

A beam of 1.8 MeV He^{+1} ions beam was used for RBS, and the information gathered was processed with SIMNRA code (Mayer, 1999) to obtain the calculation of the depth distribution of implanted species, which was then converted in concentration [at%]. These results were compared with the previous results on ion-implanted epoxy samples (Noor Azman et al., 2012).

For the work on the X-ray shielding capability of these implanted samples, a general diagnostic X-ray machine (Make: Shimadzu, Model: Circlex 0.6/1.2 P364DK-100SF), a DIADOS diagnostic detector and a DIADOS diagnostic dosimeter (PTW-Freiburg, Germany) were used. The DIADOS dosimeter is a universal dosimeter for measuring simultaneous dose and dose rate for radiography, fluoroscopy, mammography, dental X-ray and CT with a minimal dose sensitivity of 0.01 microRoentgen (μR). The incident X-ray dose (D_0) was measured by placing the detector directly below the X-ray tube at a distance of 100 cm. The exit dose (D) was measured by placing the sample on the detector. The X-ray beam was well collimated to the size of the sample and the exposure was set at 10 mAs to receive significant readings for this type of detector. The range of X-ray tube voltage (40–100 kV) was selected for this investigation since this range is the normal range of X-ray tube voltage used for the general diagnostic imaging purposes. The linear attenuation coefficient, μ (unit: cm^{-1}) for each sample was determined from Eq. (1) where x is the thickness of the sample.

$$\mu = \frac{\ln(D_0/D)}{x} \quad (1)$$

3. Results and discussion

The list of samples implanted with different ions is shown in Table 1. Fig. 1 shows the RBS results plotted as the yield versus channel number for acrylic and glass samples (B1–C3) implanted with W and Pb.

The RBS composition of acrylic and glass was used to calculate the range of implanted ions, using Monte Carlo simulation (SRIM 2010). The range of 122.8 keV W in acrylic is 84 nm and in glass is

Table 1
List of polymer composites and glass prepared with different implanted ions and their concentrations. For comparison reasons, we included previous results on the epoxy.

Sample ID	Matrix	Nominal dose [ions/cm^2]	Implanted Ion	RBS ion concentration [at%]
A1	Epoxy	7.0×10^{14}	W	0.055
A2		7.0×10^{14}	Pb	0.250
A3		1.4×10^{15}	Pb	0.390
B1	Acrylic	7.0×10^{14}	W	0.050
B2		7.0×10^{14}	Pb	0.200
B3		1.4×10^{15}	Pb	0.430
C1	Glass	7.0×10^{14}	W	0.100
C2		7.0×10^{14}	Pb	0.290
C3		1.4×10^{15}	Pb	0.850

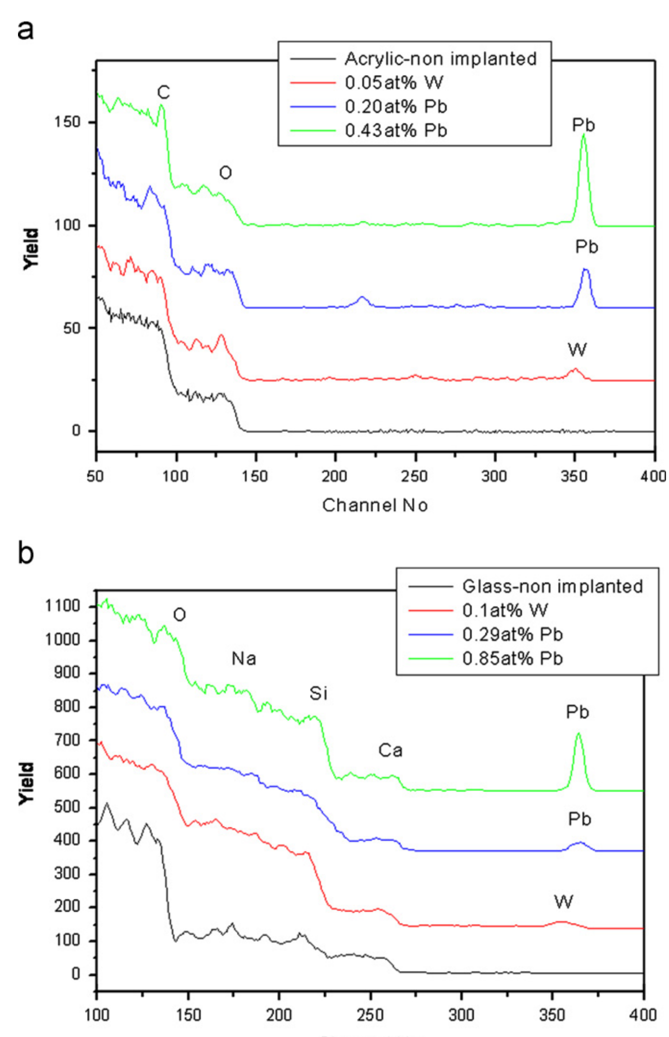

Fig. 1. RBS result for (a) acrylic implanted samples B1 (W), B2 and B3(Pb); and (b) glass implanted samples C1 (W), C2 and C3 (Pb).