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Novel fluorescent nuclear track detector technology for mixed neutron-gamma fields

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ABSTRACT

The latest achievements in fluorescent nuclear track detector (FNTD) technology are described. FNTDs are aluminum oxide crystals containing aggregate oxygen vacancy defects and doped with carbon and magnesium (Al_2O_3:C,Mg). Unlike most nuclear track detectors, Al_2O_3:C,Mg is sensitive to low linear energy transfer (LET) radiation including secondary electrons resulting from interactions of photons with the crystal. A new image processing method is investigated as a technique to discriminate and measure the doses of gamma and fast neutrons in mixed field conditions. Dose dependencies for both gamma and neutron irradiated FNTDs are shown. The new image processing method increased the dynamic range of detectable neutron doses from 4 orders of magnitude for track counting method to at least 6 orders of magnitude by combining track counting with the new image processing method. The new image processing method is combined with a detector configuration utilizing three converters: Teflon®, polyethylene, and lithium fluoride.

1. Introduction

Landauer Inc. has recently developed a novel fluorescent nuclear track detector (FNTD) technology suitable for replacing plastic nuclear track detectors (PNTD) for neutron dosimetry (Akselrod et al., 2006a,b). FNTDs are aluminum oxide crystals containing aggregate oxygen vacancy defects and doped with carbon and magnesium (Al_2O_3:C,Mg). The crystals are imaged using laser scanning confocal fluorescence microscopy. Radiation-induced tracks appear as bright fluorescence features on dark background and are due to radiochromic transformation of aggregate defects – F_2^{2+}(2Mg) centres, into F_2^{+}(2Mg) colour centres (Akselrod et al., 2003).

The F_2^{+}(2Mg) centre has three excited states identified by their absorption/excitation bands centred at 4.8 eV (260 nm), 3.7 eV (335 nm) and 2 eV (620 nm). When the F_2^{+}(2Mg) centre is optically stimulated into one of its excited states, the electron will relax back to its ground state with a 75 ns lifetime, emitting a 750 nm photon (Akselrod et al., 2003). It is important to emphasize that this process is not optically stimulated luminescence (OSL), which consists of two steps – photoionization of traps filled during irradiation and recombination of free charge carriers with luminescence centres (Bøtter-Jensen et al., 2003). In FNTD technology, laser-induced fluorescence (also known as photoluminescence) is employed. This fluorescence is intra-centre luminescence produced as a result of an excitation and radiative relaxation process that occurs without photoionization of the colour centre (Fowler, 1968). The result of irradiation is measured by detecting the intensity of radiation-induced fluorescence. The intensity is proportional to the number of radiochromically transformed F_2^{+}(2Mg) centres (Akselrod et al., 2006a,b). The short 75 ns decay time of the F_2^{+}(2Mg) centre makes it possible for fast laser scanning and imaging of the detector.

Track detectors, including FNTDs, have traditionally measured neutron dose by relating track density of nuclear reaction products to the incident neutron fluence. Unlike most nuclear track detectors, Al_2O_3:C,Mg is sensitive to low linear energy transfer (LET) radiation including secondary electrons resulting from interactions of photons with the crystal. This paper will demonstrate that FNTDs can be used to image overlapping secondary delta electron tracks and image processing can be used to determine the photon dose.

Neutron radiation is usually accompanied by gamma radiation, and a high contribution of gamma to radiation-induced fluorescence signal might be a problem for neutron detection. If the dose of gamma radiation is above several cSv, then the fluorescence induced by overlapping secondary delta electron tracks can interfere with the signal induced by recoil protons making it difficult to detect and count neutron-induced tracks. A new image processing

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method is investigated in this paper as a technique to determine the correct dose in mixed gamma-neutrons fields. The new image processing method is combined with a new detector configuration utilizing three converters of non-ionizing to ionizing radiation to effectively separate neutron and gamma induced signals.

2. Materials and methods

2.1. Detector preparation

FNTDs were cut from single Al_2O_3:C,Mg crystals in the form of $6 \times 4 \times 0.5$ mm^3 rectangular plates with the long side aligned along the optical *c*-axis of the crystal. One large side of the FNTD was polished. All FNTDs were thermally annealed and optically bleached to enhance track counting performance (Sykora and Akselrod, 2010) and to eliminate most of the background signal for improving the lowest detectable dose.

Because neutrons are not directly ionizing radiation and Al_2O_3 detectors are sensitive only to ionizing radiation, neutron converters are necessary. In the case of fast neutrons, high-density polyethylene (HDPE) is used because of its high concentration of hydrogen (Attix, 1986). Fast neutrons collide with bonded hydrogen atoms via elastic scattering and produce recoil protons which escape from the converter, penetrate the crystal and produce ionization. The range of recoil protons in aluminum oxide varies from a fraction of a micron to several hundred microns depending on neutron energy, depth of interaction in HDPE, and angle of neutron incidence.

In the case of thermal neutrons, there are a number of different materials with high thermal neutron capture cross-sections such as ^{6}LiF. The corresponding nuclear reaction is as follows:

$$^6\mathrm{Li} + {}^1n \rightarrow {}^4\mathrm{He}(2.05\ \mathrm{MeV}) + {}^3\mathrm{H}\ (2.73\ \mathrm{MeV}) \quad (1)$$

The alpha particle (^{4}He-ion) and tritium ion generated according to the this nuclear reaction have a maximum range in Al_2O_3 of 4 and 24 μm respectively and can be efficiently detected using FNTD technology because of the particles high energy and relatively long range.

For irradiations with neutrons and gamma, detectors were mounted in a high density polyethylene (HDPE) holder specifically designed to cover half of the polished side of the FNTD with 800 μm of HDPE and the other half with either ^{6}LiF (TLD-100 chip) or a 1 mm thick piece of Polytetrafluoroethylene (PTFE or Teflon®). The efficiency of recoil production in PTFE is negligible compared to HDPE, therefore PTFE acts as an absorbing layer for electron equilibrium during photon irradiation. Fig. 1 illustrates the configuration of an FNTD in contact with the three converters. Only data

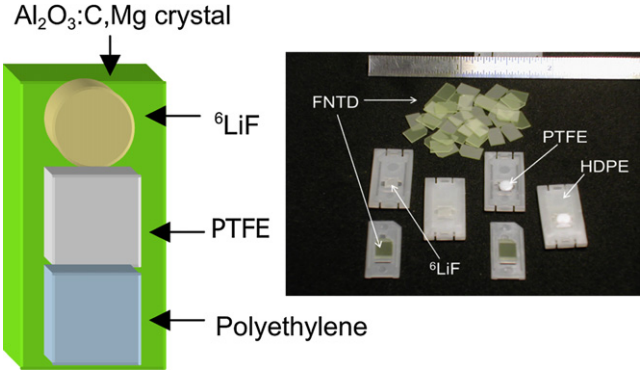

Fig. 1. Diagram of FNTD detector configuration with three converters for measurement and discrimination of fast neutron, thermal neutron and gamma and the photo of open HDPE package with Al_2O_3:C,Mg crystal designed for two converters.

pertaining to the detection of fast neutrons and FNTDs covered with HDPE and PTFE are presented in this paper.

2.2. Irradiations

Irradiations were performed at the Landauer irradiation facility in Glenwood, IL. FNTD-converter combinations were irradiated in three groups; group one was irradiated with neutrons only, group two was irradiated with gamma only and group three was irradiated with a combination of neutron and additional gamma. A fourth group was left as a control. FNTDs in groups one and three were exposed to fast neutrons from a ^{241}AmBe source with mean neutron energy of 4.4 MeV.

To reduce gamma contribution to the neutron field the source is surrounded by 3 mm of steel and 2 mm of lead. A fast burst reactor with mean neutron energy about 1 MeV was used to produce high neutron doses which were corrected by the energy dependence of FNTDs (Sykora et al., 2009). In all cases gamma component of the neutron fields was measured and FNTD signal was corrected according to the developed algorithm.

Fast neutron doses in the range of 0.1 mSv–12 Sv in terms of personal dose equivalent, $H_p(10)$, were delivered to the FNTDs in group one. FNTDs in group two were exposed to gamma photons in a wide dynamic range of doses between 30 mSv and 10 Sv from a ^{137}Cs source. Group three was irradiated with fast neutron doses of 30 and 100 mSv and gamma doses of 10 mSv, 30 mSv or 100 mSv to provide neutron to gamma ratios of 10:1, 3:1, 1:1 and 1:3 in terms of personal dose equivalent.

2.3. Readout and image processing

All FNTDs were scanned with an in-house built optical imaging system. The confocal scanning system was designed to obtain fluorescence images from the detectors with diffraction-limited resolution. Two-axis galvanometer mirrors were used for fast scanning in the XY plane. Axial (Z) scanning and focal point depth positioning in the crystal is provided by a piezo-actuator stage. The fluorescence excited by the laser light is collected by the same objective lens, transmitted back through the dichroic mirror, imaged on a confocal pinhole and detected by a silicon avalanche photodiode (APD) installed behind the pinhole. An additional optical filter in front of the APD rejects residual laser light. The confocal pinhole is a spatial filter that blocks all fluorescence originating outside of the focal spot of the objective lens and provides diffraction limited spatial discrimination. Images are formed as an array of voltages obtained by the data acquisition board from the photodetector. The imaging system is designed specifically for 639 nm excitation and 750 nm fluorescence. The optical system was built for fast automatic scanning; more details can be found elsewhere (Akselrod et al., 2006a).

During readout, FNTDs were first scanned perpendicular to the detector surface to detect the surface position with an accuracy of 100 nm. After the axial surface position was found, the detectors were scanned in a plane parallel to their surface at a depth of 3.5 μm below the surface of the crystal. Single images had dimensions of 100×100 μm^2 and the number of acquired images depended on the measured dose and was adaptively varied between 45 and 150 for each of the converter areas.

Images were processed using automatic image processing software developed in a LabView™ programming environment. Tracks were automatically identified and counted, and the dose was calculated as a function of track density. A new image processing algorithm was developed to analyze the spatial frequencies and fluorescence intensity distribution of the image. The result of this analysis will hereby be referred to as the image power. The image power was calculated in parallel with track counting.