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Effects of 7 MeV proton irradiation on microstructural, morphological, optical, and electrical properties of fluorine-doped tin oxide thin films

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A R T I C L E I N F O

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1. Introduction

Spacecrafts operating in the deep space environment continuously encounter various types, energies, and doses of ionizing radiations [1,2]. The most common and abundant species of ionizing radiations found in the deep space environment are protons, electrons, neutrons, γ-rays, and heavy nuclei with charges ranging from $Z = 3$ (lithium) to approximately $Z = 28$ (nickel) [1–3]. Much as ions heavier than nickel are also known to exist in the deep space environment, their relative abundances significantly drop after iron (Fe) [1,3], making them less significant. The ionizing radiations found in space environments majorly emanate from galactic sources [1,4], particles trapped in Earth's atmosphere [2], and from the Sun as solar particles [2–4].

During a spacecraft's operational lifetime, ionizing radiations can interact with the spacecraft components and cause significant simple point (vacancies and interstitials) and line (dislocation lines) defects in the microstructures of the bombarded material [5]. Depending on the radiation type, energy, dose, and the atomic mass and density of the target, the simple defects can evolve into more complex defect structures such as planar (stacking faults, deformation and transformation twins, and dislocation loops) and volume (precipitates, segregates, bubbles, and voids) defects [5–7]. Irradiation-induced defects are perilous issues associated with physical effects such as hardening, swelling, creep, and embrittlement, which in turn can contribute to the failure of materials in an intense radiation environment [8]. Other consequences of irradiation include the production of phonons, excitons, and plasmons, secondary electrons and photons, heating of the material, and in some cases the formation of adatoms and ripples on surfaces [6,9].

Being positively charged, protons interact with and dissipate energies in a material primarily through the electronic and nuclear energy loss mechanisms [10]. The electronic energy loss, also referred to as the ionization energy loss dominates in the high energy regime [11]. Here, the incident ions transfer energy through coulomb inelastic collisions with atomic electrons, leading to excitation and/or ionization of the target atoms [11,12]. On the other hand, nuclear energy loss, also commonly known as non-ionizing energy loss (NIEL) dominates in the low energy regime [11,12]. In the NIEL process, incident ions lose energy through elastic collisions with atomic nuclei. If the energy transferred to a target atom is more than the lattice displacement energy of the target material, atomic displacement takes place, else the primary

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