ACCELERATOR-DRIVEN RADIATION STUDIES OF YSZ-MgO COMPOSITES FOR NUCLEAR APPLICATIONS

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Abstract

YSZ and YSZ-MgO thin films were deposited on Si (100) substrates using RF sputtering and RF-DC co-sputtering techniques and studied under low-energy heavy-ion irradiation. Two sets of films were prepared: YSZ sputtered in argon environment and YSZ and Mg co-sputtered in argon and oxygen environment. Irradiation studies show enhanced crystallinity in single-component YSZ and significant degradation of YSZ crystallinity in YSZ-MgO films. These results indicate a strong dependence of radiation response on composition of the material.

INTRODUCTION

Materials employed in radiation environments, including nuclear reactors, outer space, and accelerator laboratories, are subjected to extreme radiation conditions. Such exposure results in radiation-induced damage, which severely affects the structural integrity of the materials and shortens their operational lifespan. Therefore, the development of materials with superior radiation tolerance has become critically important. In this context, a thorough understanding of the behaviour of materials under irradiation is essential for designing advanced materials with enhanced resistance to radiation-induced degradation.

Composite materials have recently attracted attention as they are expected to exhibit enhanced radiation tolerance compared to their single-component counterparts due to the presence of heterointerfaces. It has been reported that heterointerfaces in composites serve as more efficient defect sinks than the grain boundaries present in single-component materials [1].

A major challenge in the nuclear industry is the safe management of waste containing plutonium and minor actinides, which contribute to long-term radiotoxicity [2,3]. The inert matrix fuel (IMF) concept addresses this issue by incorporating PuO_2 and MAs into UO_2-free inert matrices to enable their transmutation [4]. IMF materials must possess high radiation resistance, thermal conductivity, chemical and thermal stability, low neutron absorption cross-section, and compatibility with fuel components [5]. YSZ and MgO are well-studied radiation-resistant materials, with YSZ considered a promising IMF candidate. However, YSZ has lower thermal conductivity, limiting its application. To overcome this, MgO can be combined with YSZ to form composites with improved thermal conductivity and potentially enhanced radiation tolerance [6]

Radiation damage in materials can be studied using various approaches, such as in-pile irradiation in nuclear reactors, investigation of natural analogues through actinide doping, computer simulations, and ion irradiation using particle accelerators [7]. Among these methods, accelerator-based ion irradiation is considered one of the most efficient techniques for examining radiation-induced damage. By carefully selecting the ion species and energy, ion beams can effectively mimic the radiation damage produced in materials under extreme environments [7].

This work investigates the radiation response of YSZ and YSZ-MgO thin films under low-energy heavy-ion irradiation at room temperature. The study aims to understand how the radiation response of a composite material differs from that of a single-component material.

EXPERIMENTAL TECHNIQUES

YSZ and YSZ-MgO thin films were deposited on Si (100) substrates using RF and DC sputtering techniques. Prior to deposition, substrates were cleaned using a standard procedure to avoid contamination. In Set 1, YSZ thin films were prepared by RF sputtering of a ZrO_2 (8 mol% Y_2O_3) target at 3×10^{-2} mbar and 573 K, using 100 W RF power for 2 h in an argon atmosphere (30 sccm). In Set 2, YSZ-MgO films were grown by RF co-sputtering of YSZ and DC sputtering of Mg in an argon and oxygen atmosphere (15 sccm each), at 1×10^{2} mbar and 673 K, using 120 W RF and 50 W DC power for 2 h. The deposited films were characterized using GIXRD for phase identification and composition analysis. For irradiation studies, Set 1 film were irradiated with 200 keV Kr ions at 5×10^{16} ions/cm^2, while Set 2 films were irradiated with 100 keV Kr ions at 1×10^{16} ions/cm^2 using the LEIBF facility at IUAC, New Delhi. Low-energy heavy ions are selected because they can effectively simulate the damage caused by alpha-recoil nuclei present in nuclear reactor environments. Post-irradiation characterization was carried out using GIXRD.

RESULTS AND DISCUSSIONS

Figure 1 shows the GIXRD patterns of the synthesized thin films. The YSZ thin film exhibits a fluorite-type cubic phase. The thin film synthesized using YSZ and Mg targets in an oxygen and argon environment (Set 2) exhibits the formation of a distinct crystalline MgO phase along with a significant reduction in the crystallinity of the YSZ phase.

The YSZ thin films were irradiated with low energy 200 keV Kr ions. The nuclear energy loss (S_n), electronic energy loss (S_e), and projected range of 200 keV krypton ions in YSZ are 2.24 keV/nm, 0.37 keV/nm and 62±24 nm respectively. From the GIXRD patterns of pristine and irradiated YSZ thin films (Set 1) shown in Figure 2, it is observed that irradiation leads to grain growth or an improvement in crystallinity.

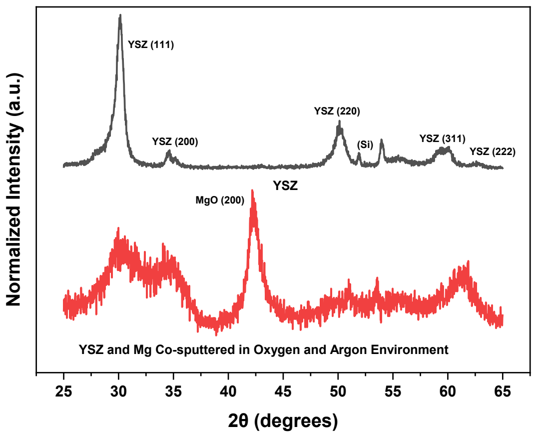

Figure 1: GIXRD of as-deposited thin films (pristine thin films).

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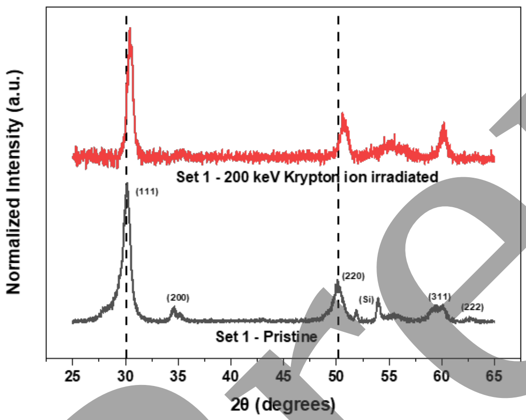

Figure 2: GIXRD pattern of pristine and irradiated YSZ thin films.

YSZ-MgO thin films deposited by co-sputtering of YSZ and Mg targets in oxygen and argon environment (Set 2) were irradiated with 100 keV Kr ions. The S_n, S_e and projected range of 100 keV Kr ions in YSZ are 2.34 keV/nm, 0.36 keV/nm and 33±14 nm, respectively. GIXRD patterns of pristine and irradiated thin films are given in Figure 3. These films exhibit a drastic reduction in the crystallinity of the YSZ after irradiation. The crystallinity of the MgO phase however remains almost unchanged.

These behaviours indicate a strong dependence of radiation response on film composition. However, the underlying mechanisms responsible for these variations cannot be fully established from structural analysis alone. Therefore, further detailed characterizations, including microstructural, compositional, and defect-level investigations, are necessary to elucidate the exact origin of the observed irradiation-induced effects in these thin films.

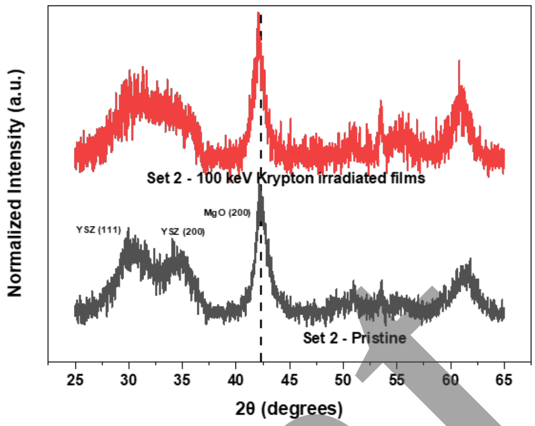

Figure 3: GIXRD pattern of pristine and irradiated YSZ-MgO thin films.

CONCLUSION

The radiation response of YSZ and YSZ-MgO thin films varies significantly with composition. YSZ shows irradiation-induced improvement in crystallinity, while YSZ and Mg co-sputtered thin films in argon and oxygen environment exhibits marked degradation of YSZ crystallinity. These differences suggest distinct defect evolution mechanisms. Further detailed microstructural and defect-level studies are required to fully understand the observed behaviour.

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