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SHORT COMMUNICATION

Sustainability of Fluorine-Tin Co-Doped Indium Oxide (F,Sn:In2O3) Nanocrystals at Various Shock Speeds Under Dynamic Shocked Conditions

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Abstract
In the current investigation, fluorine tin co-doped indium oxide (F, Sn: In_2O_3) cubic-shaped nanocrystals were put through dynamic shock wave recovery studies in order to evaluate the structural performance of these nanocrystals under harsh conditions. Despite being exposed to a shock wave with a Mach number of up to 6.2 at a variety of shock speeds, the F, Sn: In_2O_3 nanocrystals were able to maintain their original crystal structure, as demonstrated by the findings.

Keywords Nanocrystals · Shock Waves · Morphology · XRD · F · Sn:In_2O_3

Introduction

Indium oxide, also known as In_2O_3, is a transparent conducting oxide that has been extensively researched and is well-known for its uses in solar cells, flat-panel displays, and a variety of other optoelectronic devices [1]. It is one of the materials that has received a substantial amount of attention because of its intrinsic features, such as high electrical conductivity and optical transparency, while obtaining extreme optical absorption properties in the infrared range [2, 3]. (F, Sn: In_2O_3) offers significant advantages for optoelectronic applications due to its enhanced electrical conductivity, improved optical transparency, and superior thermal and structural stability. Electro-optical measurements require low resistivity (~10 Ω/sheet) and excellent transparency for optimal high-frequency functioning [4]. Because of these properties, the material can be used in systems and devices that utilise high-performance optoelectronics. With these unique infrared absorbing properties, F,Sn: In_2O_3 nanocrystals may be used in aerospace defence stealth material surfactant materials to reduce infrared signature footprint via optical extinction. However, in the pursuit of sustainable and resilient materials in such extreme hypersonic shock conditions, the nanocrystalline and structural stability of these nanocrystals under variable shock speed extreme environments should be evaluated.

A situation that mimics the high-pressure conditions [5] that materials could face in real-world applications is dynamic shock loading [6]. Shock waves are pressure fronts that are extremely powerful and high in energy [7]. The objective of this research is to evaluate the viability of F, Sn: In_2O_3 nanocrystals when subjected to dynamic shock conditions.

Materials and Methods

Synthesis of F, Sn: In_2O_3

The nanocrystal is synthesized via continuous injection colloidal synthesis for nanocrystal growth. The detailed synthesis procedure is already reported in [8, 9].

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Shock Tube Details

In order to attach the F, Sn: In_2O_3 nanoparticles to a test model of the shock tube end wall, double-sided tape served the purpose. An acrylic tube with an internal diameter of 4.7 cm served as the test model. This dimension is comparable to the inner diameter of the tube that was being driven along. The detailed information is already published in [10].

Results and Discussion

XRD Analysis

To confirm the structural properties of F, Sn: In_2O_3 nanocrystal, XRD analysis has been performed. The results confirm the XRD pattern with ICSD Code # 00-006-0416 (Fig. 1) [8]. In the absence of any further metastable indium oxide phases, the principal indium oxide peaks (222), (400), (440), and (622) of the bixbyite phase were all found to be in their initial form. Figure 1, shows that no noticeable change can be observed under shocked conditions when shock speeds are varied. The diffraction peak remains mostly unchanged regardless of the shock speeds. Nonetheless, it moves slightly toward the plane's lower diffraction angle (222), as shown in Fig. 1(b). The (222) peak moving toward lower 2Θ values is due to strain changes in the crystal lattice and the substitution of indium sites with Sn^{4+} ions due to its smaller radius (0.71 Å). Furthermore, the findings indicate that the full-width half maximum (FWHM) values for the sample's (222) plane are 0.7495 (a = 10.1120 Å), 0.7499 (a = 10.1223 Å), and 0.698 (a = 10.1275 Å) when the shock speeds are 1.96, 2.32, and 1.64 km/s, respectively. This demonstrates that the crystalline integrity of F, Sn: In_2O_3 nanocrystals is essentially unaffected by the shock wave conditions.

SEM Analysis

Figure 2 displays SEM images of F, Sn: In_2O_3 nanocrystal powder that has been bombarded with shock waves. All of the hypersonic shock cycle samples maintained a cubic-shaped nanocrystal size and morphology under exposure at shock speeds of 1.96, 2.32, and 1.64 km/s. The average particle sizes were 13.65, 12.83, and 13.65 nm, respectively. When subjected to different shock speeds, particle size remains rather constant. F, Sn: In_2O_3 nanocrystals show remarkable resistance to dynamic shock loading, as evidenced by their cubic shape and constant particle size over a range of shock velocities. Due to their consistent size and shape, nanocrystals have steady mechanical characteristics that guarantee their dependable performance in real-world applications that expose them to comparable stress. Material deterioration during stress exposure might jeopardize the performance of optoelectronic devices and other complex technological applications, making this stability critical. Thus, the results of the SEM study support the conclusions drawn from the XRD results, which indicate that the F, Sn: In_2O_3 nanocrystals exhibit remarkable stability and resilience in morphology.

XPS Analysis

The deconvolution peaks shown in Fig. 3(a-c) in all the shock-loaded samples at $3d_{5/2}$, $3d_{3/2}$ doublet, and $3p_{1/2}$ indicate that the incoming shock wave causes indium to undergo

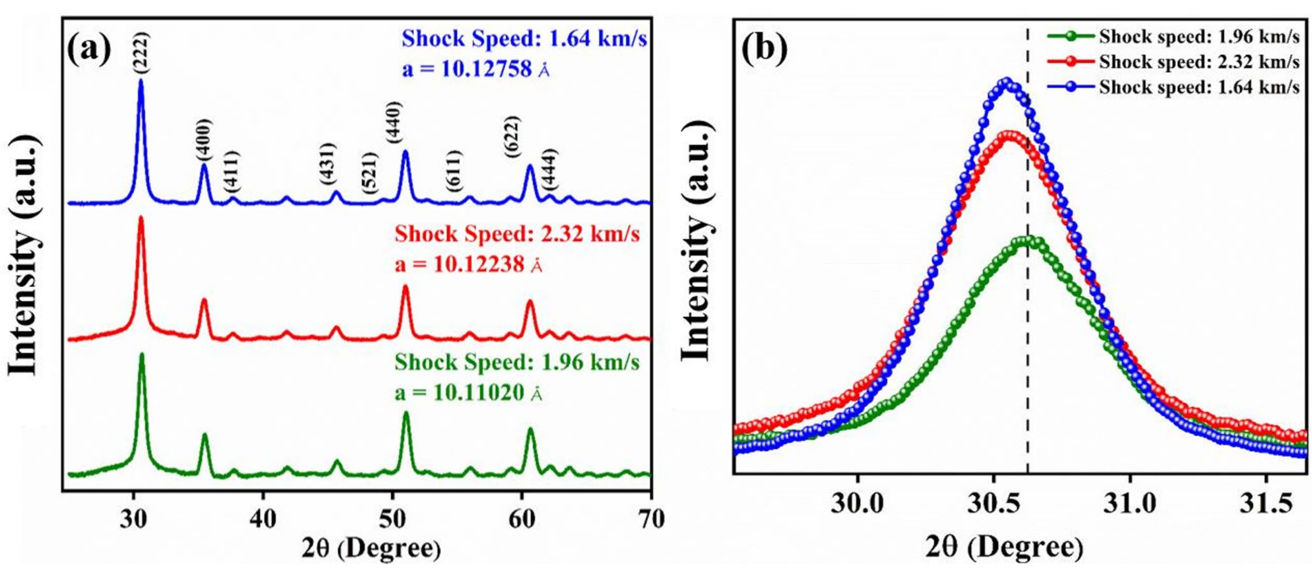

Fig. 1 XRD pattern of **(a)** shock cycle exposed F, Sn: In_2O_3, **(b)** zoomed view of (222) peak

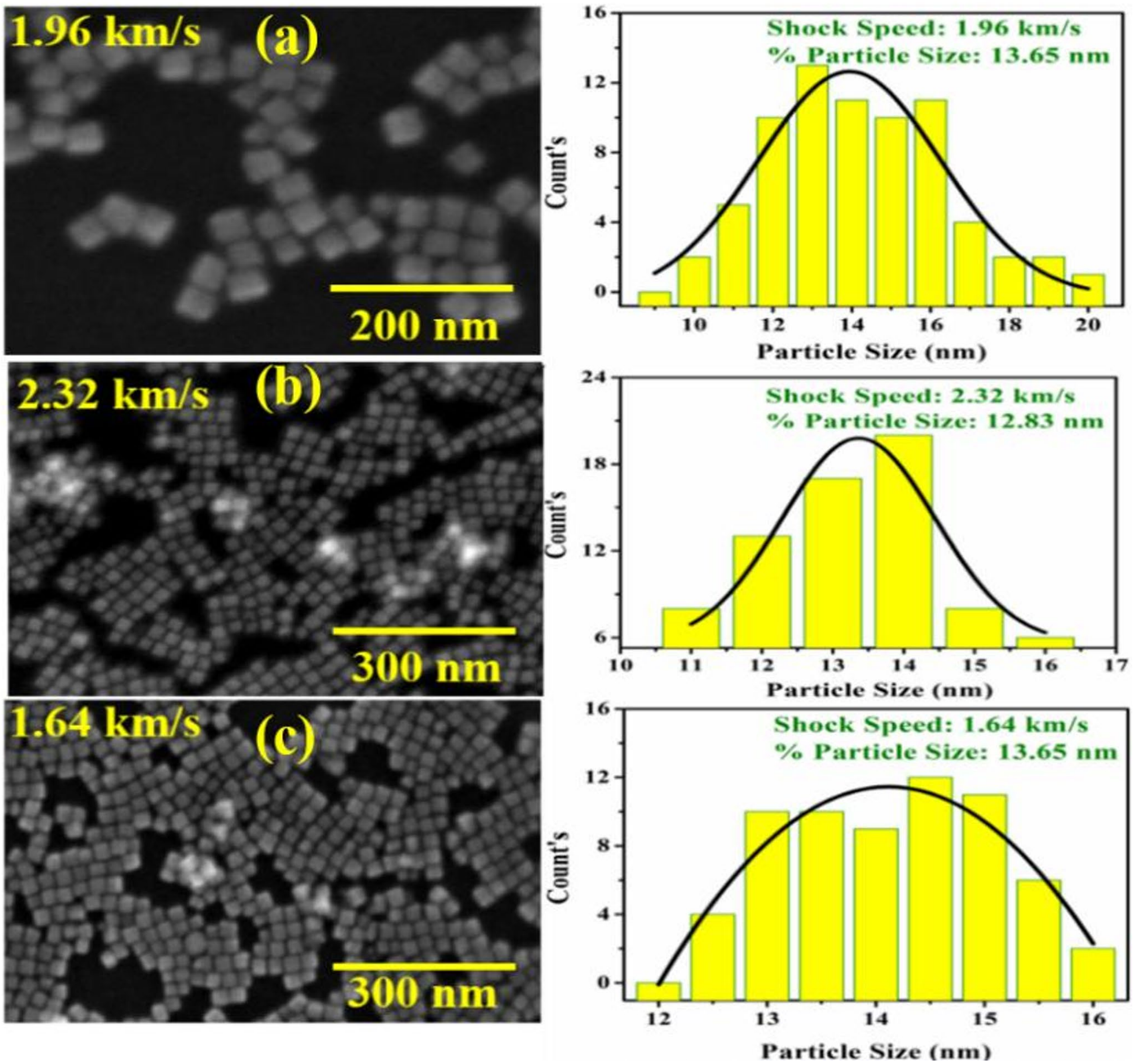

Fig. 2 SEM images and average particle size of F, Sn: In_2O_3 nanocrystal **(a)** 1.96 km/s, **(b)** 2.32 km/s, **(c)** 1.64 km/s

three surface oxidation state species: metallic state In, oxidated In_2O_3, and hydroxylated $In(OH)_3$ [11]. These observations show that the infrared electromagnetic radiation that was incident on the samples caused surface oxidation states to be created without causing any changes to the materials' underlying chemical composition. It is important to note that the binding energies of these peaks did not undergo any substantial changes across all of the shock-loaded tested samples. This suggests that the chemical states of the elements remained constant despite being subjected to different shock speeds. They are able to keep their electronic structure and chemical integrity intact, which is essential for their prospective uses in high-stress environments such as aerospace technology.

Conclusion

A comprehensive investigation into F, Sn: In_2O_3 nanocrystals under dynamic shock wave conditions indicates the exceptional stability and durability of these nanocrystals. The findings of the XRD reveal that the FWHM for the (222) plane show negligible fluctuation across varied shock speeds. SEM analysis further supports the results, which show that the nanocrystals keep their faceted morphology

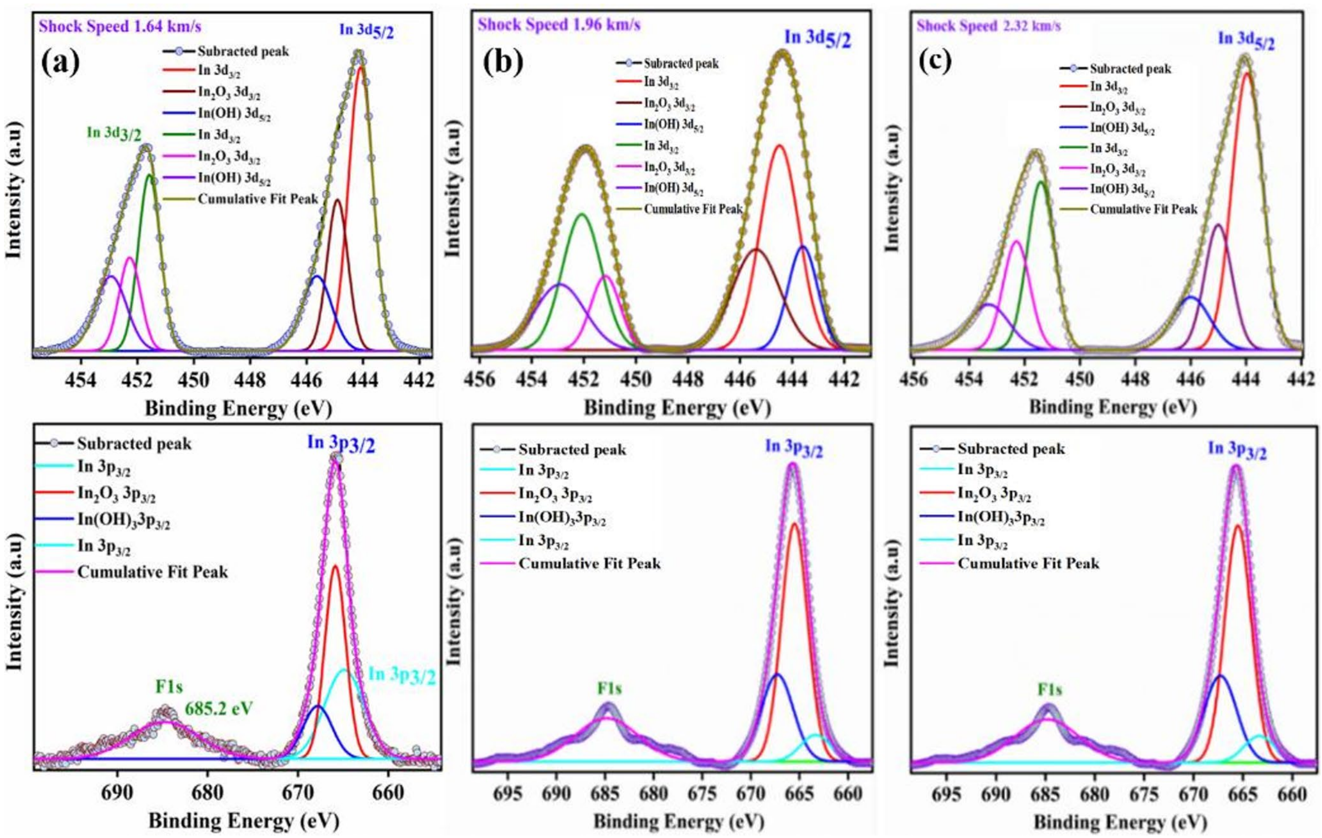

Fig. 3 XPS deconvolution for shock speed **(a)**1.64 km/s, **(b)**1.96 km/s, **(c)**2.32 km/s F, Sn: In_2O_3 nanocrystals

and cubic form with average particle sizes of 13.65, 12.83, and 13.70 nm. The nanocrystals exhibit remarkable morphological stability as evidenced by their consistent particle size and shape under different shock flow conditions. Additionally, the deconvolution of XPS peaks reveals metallic indium (In), oxidized indium oxide (In_2O_3), and hydroxylated indium hydroxide ($In(OH)_3$), with no significant binding energy variations across shock speeds. Chemical state and electronic structure stability reinforce the material's toughness. Their exceptional endurance and performance under extreme conditions make them ideal candidates for cutting-edge optoelectronic and hypersonic aerospace vehicles.

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Declarations

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this manuscript.

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