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**Fluorinating reagents are used to model interfacial reactions in fluoride-ion batteries. Topochemical F-ion insertion is seen for one-dimensional (1D) tunnel-structured  $\text{FeSb}_2\text{O}_4$  but interphase formation comprising antimony (oxy)fluorides is observed for  $\text{MnSb}_2\text{O}_4$ .**

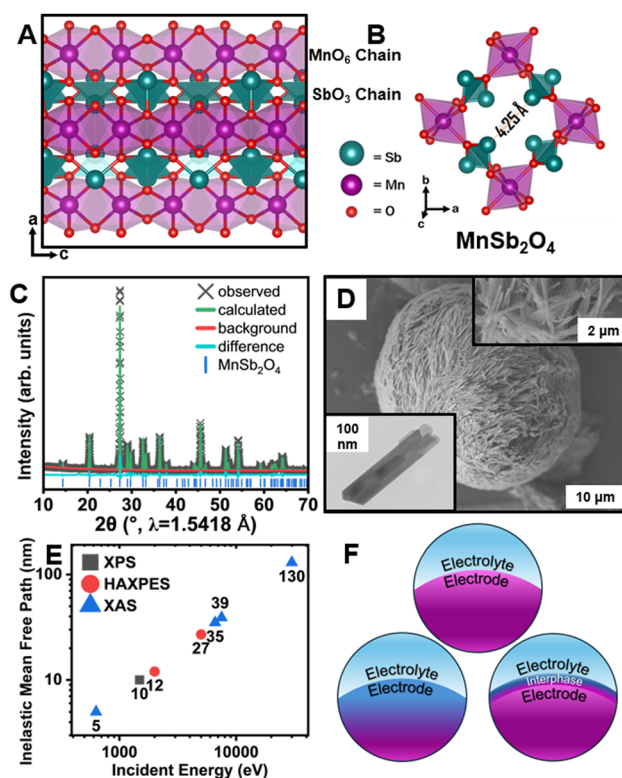
Grid-level energy storage requires a diversity of battery chemistries so as to alleviate stresses on current mineral supply chains and to provide safer alternatives to Li-ion batteries.<sup>1–3</sup> “Beyond Li” alternatives such as Na-ion batteries are yet to realize comparable energy densities, and often do little to diversify materials palettes.<sup>4,5</sup> Fluoride-ion batteries, which implement fluoride anions as charge carriers have received considerable attention as an orthogonal alternative with the potential to alleviate supply chain challenges and preclude the need for metal electrodeposition.<sup>6–10</sup> Fluoride conversion electrodes have shown promise but challenges remain with regards to high temperatures for successful operation, large volume changes, and sluggish fluoride-ion diffusion.<sup>6–8</sup> Much recent attention has focused on the design of insertion-based fluoride electrode materials where the integrity of the structural framework of insertion electrodes is preserved upon F-ion insertion/deinsertion.<sup>11</sup> However, a key consideration is the competition between ion insertion and interphase formation.<sup>12</sup> Here, we use fluorinating reagents,  $\text{XeF}_2$  and  $\text{NOBF}_4$ , as models for interfacial electrode reactions to contrast F-ion reactivity in 1D tunnel-structured  $\text{FeSb}_2\text{O}_4$  and  $\text{MnSb}_2\text{O}_4$ , which both adopt the schafarzikite-type structure but with distinctive oxidation potentials (0.771 and 1.56 vs. standard hydrogen electrode (SHE) for  $\text{Fe}^{2+}/\text{Fe}^{3+}$  and  $\text{Mn}^{2+}/\text{Mn}^{3+}$ , respectively).<sup>13</sup> We utilize a broad suite of spectroscopic methods to probe chemical reactivity in model F-ion

# Interphase formation *versus* fluoride-ion insertion in tunnel-structured transition metal antimonites†

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insertion hosts to differentiate between interphase formation and insertion reactions.

The schafarzikite-type  $\text{MA}_2\text{O}_4$  structure sketched in Fig. 1 (M = transition metal, A = p-block element with stereochemically active lone pairs) forms 1D tunnels defined by corner-shared



**Fig. 1** Structure and characterization of  $\text{MnSb}_2\text{O}_4$ . (A) Schafarzikite-type  $\text{MnSb}_2\text{O}_4$  viewed along (010); (B) 1D tunnel of  $\text{MnSb}_2\text{O}_4$  viewed along the *c* direction. (C) Rietveld-refinement to powder XRD pattern used to obtain the structures in (A) and (B). (D) SEM image of  $\text{MnSb}_2\text{O}_4$  nanorods; top inset shows magnified SEM; bottom inset shows a TEM image. (E) IMFP of an electron calculated based upon the incident energy for XPS, HAXPES, and XAS measurements. (F) Schematic illustration of F-ion reactivity.

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[MO<sub>6</sub>] octahedra and [AO<sub>4</sub>] tetrahedra.<sup>14–16</sup> The stereochemical activity of 5s<sup>2</sup> electron lone pairs of Sb<sup>3+</sup> cations defines a large one-dimensional tunnel with an abundance of interstitial sites that can accommodate F-ions (Fig. 1B). In FeSb<sub>2</sub>O<sub>4</sub>, electron lone pair repulsions mediate frustrated coordination and ensure low site-to-site diffusion barriers whilst redox compensation is engendered through formal oxidation of Fe centers upon F-ion insertion.<sup>14</sup> The greater oxidation potential of the d-block cation in MnSb<sub>2</sub>O<sub>4</sub> holds promise for accessing a higher voltage but the more challenging redox also renders parasitic reactions more probable.<sup>17</sup> While reversible room-temperature F-ion insertion with stoichiometries up to  $x \approx 1$  can be accessed for FeSb<sub>2</sub>O<sub>4</sub>F<sub>x</sub>,<sup>14,15</sup> complex interphasic products are instead stabilized upon reaction with MnSb<sub>2</sub>O<sub>4</sub>.

Interphase formation at oxide surfaces has attracted much recent attention given the critical role of interphasic products in mediating ion transport, surface stresses, and preservation of electrolyte/electrode connectivity.<sup>18,19</sup> Little is known about interphase formation in anion batteries. Here, we use diverse X-ray absorption and emission spectroscopy probes of varying penetration depth (Fig. 1E) to examine interphase formation in MnSb<sub>2</sub>O<sub>4</sub> (Fig. 1F).

MnSb<sub>2</sub>O<sub>4</sub> powders were obtained through a hydrothermal synthesis as described in the ESI.† A powder X-ray diffraction (XRD) pattern and Rietveld refinement is shown in Fig. 1C (see also Table S1, ESI†).<sup>20</sup> MnSb<sub>2</sub>O<sub>4</sub> is isostructural to FeSb<sub>2</sub>O<sub>4</sub> and crystallized in the tetragonal *P4<sub>2</sub>/mbc* space group. MnSb<sub>2</sub>O<sub>4</sub> affords a larger tunnel width of 4.25 Å (Fig. 1B) as compared to 4.14 Å for FeSb<sub>2</sub>O<sub>4</sub>.<sup>21,22</sup> The obtained powders adopt a single-crystalline needle-like morphology (Fig. 1D and Fig. S1, ESI†).

Fluoridation reactions were initially performed using XeF<sub>2</sub> in acetonitrile under a diverse range of conditions as described in the Methods section.<sup>17</sup> Under these conditions, FeSb<sub>2</sub>O<sub>4</sub> can be fluoridated to insert unitary fluoride ions per Fe center.<sup>14,15</sup> Powder XRD measurements and results from Rietveld refinement for fluoridation of MnSb<sub>2</sub>O<sub>4</sub> are shown in Fig. S2 and Table S2 (ESI†). Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) characterization is shown in Fig. S3 with Fig. S4 (ESI†) showing transmission electron microscopy (TEM) imaging including lattice resolved high-resolution TEM and selected area electron diffraction (SAED). Minimal changes of lattice parameters are observed in powder X-ray diffraction even though EDS elemental maps demonstrate some reactivity and remanence of fluorine-containing species. Definitive identification of the reaction products is enabled by synchrotron X-ray spectroscopy measurements, which provide a means of distinguishing insertion and interphase formation (Fig. 1F).

X-ray absorption near-edge structure (XANES) spectroscopy measurements of the as-prepared and fluoridated MnSb<sub>2</sub>O<sub>4</sub> are shown in Fig. 2. Soft X-ray (surface sensitive) Mn L-edge (*2p–3d*) spectra for XeF<sub>2</sub>-treated MnSb<sub>2</sub>O<sub>4</sub> are plotted in Fig. 2A. Corresponding Fe L-edge data for XeF<sub>2</sub>-reacted FeSb<sub>2</sub>O<sub>4</sub> are plotted in Fig. 2B. In contrast to FeSb<sub>2</sub>O<sub>4</sub>, where F-ion insertion brings about oxidation of the Fe center,<sup>14,15</sup> the Mn L<sub>3</sub>-edge spectra with a pronounced absorption at 640 eV characteristic of divalent Mn do not evidence signatures of Mn oxidation upon treatment with XeF<sub>2</sub>.<sup>23</sup> As such, both powder XRD and Mn L-edge XANES measurements do not support the notion of F-ion insertion. However, Fig. 2C shows that reaction of MnSb<sub>2</sub>O<sub>4</sub> results in the emergence of the F K-edge (*1s–2p*), characteristic of fluoride moieties at the surface. This and the EDS measurements



Fig. 2 XANES characterization of fluoridated products. XANES spectra collected for the as-prepared MnSb<sub>2</sub>O<sub>4</sub> (black) and fluoridated products (green 1:1 molar ratio of XeF<sub>2</sub>/CH<sub>3</sub>CN at 55 °C, red 1:1 molar ratio of XeF<sub>2</sub>/CH<sub>3</sub>CN at 75 °C, and blue 1:5 molar ratio of XeF<sub>2</sub> in CH<sub>3</sub>CN at 25 °C) at the (A) Mn L<sub>3</sub>-/L<sub>2</sub>-edges, (B) Fe L<sub>3</sub>-/L<sub>2</sub>-edges, (C) F K-edge, (D) Mn K-edge, and (E) Fe K-edge. Additional spectra in (F) represent the first derivative of the Mn K-edge spectra, (G) first derivative of the Fe K-edge spectra, (H) Sb M<sub>4</sub>-, O K-edges, first derivative of the Mn K-edge spectra, (I) Sb K-edge, and (J) first derivative of the Sb K-edge spectra. Panels (B), (E), and (G) are adapted with permission from Zaheer *et al.*<sup>14</sup> Copyright (2020) ACS Energy Lett.





features can be ascribed to a combination of surface insertion and interphase formation or fluoride/oxyfluoride interphases. An alternative fluoridation agent, NOBF<sub>4</sub>, has furthermore been examined because of its high oxidizing power.<sup>28</sup> NOBF<sub>4</sub> has an oxidation potential of 1.7 V vs. SHE, which is greater than the oxidation potential of Mn by 0.14 V. Fig. S7 (ESI†) shows a powder XRD pattern acquired for MnSb<sub>2</sub>O<sub>4</sub> after reaction with NOBF<sub>4</sub> in acetonitrile. The reaction does not bring about an evident change of lattice parameters (Table S3, ESI†). SEM-EDS in Fig. S8 (ESI†) provides confirmation of fluoride incorporation with Fig. S9 (ESI†) showing TEM, including lattice-resolved high-resolution TEM and SAED.

Fig. S10 (ESI†) plots a Mn L<sub>3</sub>-edge XANES spectrum acquired for MnSb<sub>2</sub>O<sub>4</sub> after treatment with NOBF<sub>4</sub>. The spectrum shows a slight shift of the white line absorption and diminution of the pre-edge feature at 639 eV. Fig. S11 (ESI†) shows Sb M<sub>4</sub>-edge and O K-edge XANES spectra for the as-prepared MnSb<sub>2</sub>O<sub>4</sub> and after treatment with a 3-molar excess of NOBF<sub>4</sub>. Similar to Fig. 2B, no shift of the white line absorption energy is observed, which indicates retention of a nominally trivalent oxidation state for Sb. However, a pronounced modification of relative intensities of features centred at 531 eV and 536 eV is suggestive of a change in the Sb local coordination environment. F K-edge XANES spectra in Fig. S11B (ESI†) indicate the presence of anionic fluoride species after NOBF<sub>4</sub> treatment. Core-level HAXPES spectra (Fig. S11B–D, ESI†) show pronounced changes suggestive of the accumulation of an interphasic product. The O 1s core level is significantly decreased in intensity as compared to overlapping Sb 3d states, indicating that there is less oxygen on the surface (Fig. S11C, ESI†). The shift in binding energy for the Sb 3d<sub>3/2</sub> core level further suggests an alteration of the surficial Sb local coordination environment. Based on these observations, the interphase layer is most-likely formed by amorphous antimony fluorides and oxyfluorides, such as SbF<sub>3</sub> or a F-rich oxyfluoride such as Sb<sub>3</sub>O<sub>2</sub>F<sub>5</sub> (Fig. S11E–G, ESI†). Table S4 (ESI†) provides balanced chemical equations for the formation of each of these species. While NOBF<sub>4</sub> is a stronger oxidizing reagent, based on the electronic structure considerations depicted in Fig. S5 (ESI†), it promotes increased antimony oxidation and exacerbates the formation of the interphasic product. Fig. S12 (ESI†) depicts crystal structures of the candidate materials but based on X-ray scattering, the interphasic products do not appear to have long-range order.

Understanding the competitive nature of insertion *versus* interphase formation is key to the design and discovery of insertion electrodes of fluoride-ion batteries. We find a sharp contrast between low-dimensional FeSb<sub>2</sub>O<sub>4</sub> and MnSb<sub>2</sub>O<sub>4</sub>, both of which crystallize in a schafarzikite-type structure with a 1D tunnel. While the former reversibly accommodates F-ions in

interstitial sites along its tunnel, the latter is characterized by very limited bulk F-insertion. The insertion of fluoride-ions is instead constrained by the formation of an interphase layer on the surfaces of the MnSb<sub>2</sub>O<sub>4</sub> particles. While Mn affords a higher oxidation potential, the overlap of Mn 3d-derived states with Sb states at the valence band edge promotes the preferential formation of amorphous antimony fluoride or antimony oxyfluoride interphasic products. Understanding the reactivity of model systems will assist in the future realization of viable F-ion insertion electrodes and full batteries.

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## Data availability

The data supporting this article have been included as part of the ESI.†

## Conflicts of interest

The authors have no conflicts of interest to declare.

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