Anion ordering and vacancy defects in niobium perovskite oxynitrides†

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Niobium perovskite oxynitrides are emerging as promising semiconductor materials for solar energy conversion processes, due to their physical properties and amenability to defect engineering. However, defect engineering in mixed-anion semiconductors such as perovskite oxynitrides is generally hindered by the absence of long-range order in the crystal lattice, a phenomenon known as anion-ordering. We demonstrate how anion ordering influences the stability and mobility of point defects in two exemplar perovskite oxynitrides, BaNbO2N and LaNbON2. Accurate first-principles calculations show that fully cis-anion orderings in BaNbO2N are more stable than fully trans-anion orderings, whereas anion orderings with mixed dimensionality may be more prevalent in the lower-symmetry LaNbON2. Anion ordering in LaNbON2 is also influenced by a pronounced A-site coordination sphere effect not observed in BaNbO2N, whereby local La-(O,N)12 coordination environments give rise to alternating LaO and LaN layers in the bulk material. Anion order was predicted to effect the redistribution of electrons upon anion vacancy creation to the cation sublattice. Diffusion barriers for O2− vacancies in trans-ordered BaNbO2N were found to be lower than those for N3− vacancies, suggesting that stabilising trans-ordered phases of BaNbO2N will yield more effective retention of nitrogen content in this material. The reverse is the case for LaNbON2, with N3− vacancy defects exhibiting more facile diffusion than O2− vacancy defects. We believe these insights will aid the emergent understanding of defect engineering in mixed-anion perovskite oxynitride semiconductors, and specifically help facilitate strategies for stabilising their nitrogen content.

Introduction

Oxynitride materials have attracted recent interest for use in applications such as pigments, dielectrics, and optoelectronic materials.1 The overlap between the band gaps of many oxynitride materials and the solar spectrum also makes them potential water splitting photocatalysts that can operate in the visible-light region.2 Several niobium oxynitride perovskites, for instance, are promising candidate semiconductors for solar energy conversion owing to their wide visible light absorption.3–6 However, niobium oxynitrides are known to be more prone to defect formation during their synthesis via nitridation, compared to other perovskite oxynitrides (e.g. tantalum oxynitrides). This is a feature, rather than a flaw. Structural defects, such as zero-dimensional defects (e.g. vacancy, interstitial and anti-site defects) and higher-dimensional defects (dislocations, grain boundaries, and volumetric defects) provide design parameters for modulating surface active sites, charge carrier mobilities, and band edge positions.7,8 Of these, zero-dimensional point defects have the strongest link to material non-stoichiometry.7 Niobium oxynitrides are therefore ideal candidates for defect engineering. For instance, the enhanced conductivity of BaNbON compared to BaTaON is suspected to arise from defect concentration in the former.9 Niobium oxynitrides also have larger absorption tails extending in the visible region of the spectrum, which is indicative of nitrogen vacancies and reduced B-site cations, compared to their tantalum counterparts.9

However, engineering structural defects in perovskite oxynitride photocatalysts, such as AM(O,N)x (M = Ti, Zr, Hf, Ta, Nb), in a controlled manner is complicated by the lack of long-range structural order in their crystal lattices. Such disorder is otherwise known as ‘anion ordering’; despite exhibiting local ordering of anions within individual MOn−2N2 octahedra, long-range structural order is lost due to the similarity between the Mm+−O2− and Mm+−N3− orbital overlaps, and hence bond lengths. The slightly larger Mm+−N3− bond length drives a predominantly cis-ordering in individual octahedra, giving rise to N3−−Mm+−O2− chains (or O2−−Mm+−N3− in the case of LaTaON2 and LaNbON2).10

References

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3. Electronic supplementary information (ESI) available: Relative energies of LaNbON, BaNbO2N, anion orderings in the presence of vacancy defects, comparison of vacancy diffusion barrier heights as a function of supercell size. See DOI: 10.1039/d1ma00122a
Anion ordering induces local distortions\textsuperscript{11} in the crystal structure, influencing the ferroelectricity,\textsuperscript{12,13} bandgap\textsuperscript{14,15} and effective charge carrier mobility of these materials.\textsuperscript{16–18}

Anion ordering in oxynitride perovskites can be categorised into the regimes of cis- or trans-ordering as illustrated in Fig. 1, as well as by the dimensionality the ordering travels in i.e. 2D/3D for cis-ordering or 1D/2D for trans-ordering. Recent research has focused on characterising the relative stabilities of these different regimes. While cis-ordering is the more stable for d\textsuperscript{0} oxynitrates, both regimes are sensitive to stoichiometry, strain, and interfacial effects. For instance, synthetic conditions and A-site cation substitution can yield fully 2D or 3D structures,\textsuperscript{16–20} For instance, increased Sr\textsuperscript{2+} doping in CaTaO\textsubscript{2}N induces partial trans-ordering, with cis-ordering becoming energetically prohibitive due to lattice strain.\textsuperscript{21} Similarly, Vonru"{u}l et al.\textsuperscript{22} have shown that >4% compressive strain stabilizes trans-ordering in bulk LaTiO\textsubscript{3}N. Ninova et al.\textsuperscript{23} have predicted that, for LaTiO\textsubscript{3}N, surface layers can favour trans-ordering due to the charge neutral stacking afforded by (LaN)-(TiO\textsubscript{2}) layers.

However, the impact of anion ordering on anion vacancy defect formation and anion vacancy diffusion remains largely unexplored in perovskite oxynitride photocatalysts. Understanding this relationship is the first step towards controlling their defect engineering for enhanced photocatalysis. Here we address this issue by demonstrating how the stability and mobility of O\textsuperscript{2−} and N\textsuperscript{3−} vacancy point defects are influenced by local anion ordering in two representative niobium perovskite oxynitrdes, BaNbO\textsubscript{2}N and LaNbON\textsubscript{2}. Vacancy defect formation energies and migration barriers are investigated systematically as a function of both cis- and trans-ordering of N\textsuperscript{3−}-M\textsuperscript{+}–N\textsuperscript{3−} (BaNbO\textsubscript{2}N) and O\textsuperscript{2−}–M\textsuperscript{+}–O\textsuperscript{2−} (LaNbON\textsubscript{2}) chains using accurate first-principles calculations. Cis-anion orderings are in general more energetically favourable than trans-orderings in these materials. However, there are secondary ordering effects that arise from the stoichiometric distribution of anions in the A-site cation coordination sphere, most prevalent for LaNbON\textsubscript{2}. We show below how both the stability and mobility of O\textsuperscript{2−} and N\textsuperscript{3−} vacancy defects are influenced by these two ordering effects.

**Computational methodology**

All calculations reported here employ the Perdew–Burke–Ernzerhof generalized gradient approximation (GGA) exchange-correlation functional, revised for solids (PBEsol),\textsuperscript{24} as implemented in the Vienna Ab initio Simulation Package (VASP) code\textsuperscript{25,26} using the projector augmented wave (PAW) method.\textsuperscript{27} A Hubbard–U correction\textsuperscript{28} has not been employed in this work, due to the non-trivial choice of selecting a +U potential that is independent of the anion ordering and vacancy defect type. All calculations employ (core)/valence configurations of Nb: [(Ne)3s/3p3d4s; O: [(He)]/2s2p; N: [(He)]/2s2p and a plane wave energy cutoff of 450 eV. Crystal structures of BaNbO\textsubscript{2}N and LaNbON\textsubscript{2} at standard conditions were obtained from the International Crystal Structure Database (ICSD crystal IDs 434770 and 247261, respectively\textsuperscript{29}), see Fig. 2. These structures are, respectively, of P\textsubscript{n}m and P\textsubscript{n}m\textsubscript{a} symmetry. However, these symmetries are only nominal; we show below that local anion orderings within each extended supercell induce differing degrees of three-dimensional anisotropy in these ideal lattice structures when they are fully relaxed. Monkhorst–Pack meshes consisting of 6 × 6 × 6 k-points were used for the 40 atom 2 × 2 × 2 BaNbO\textsubscript{2}N supercell, while 4 × 6 × 4 k-point meshes were used for 80 atom 2 × 1 × 2 LaNbON\textsubscript{2} supercell. Vacancy migration barriers were pre-optimised using the nudged elastic band (NEB) algorithm\textsuperscript{30} to a force criterion of 0.1 eV Å\textsuperscript{−1}, before being re-optimised the Climbing Image (CI-NEB) algorithm\textsuperscript{31} to a 0.05 eV Å\textsuperscript{−1} criterion. Five images were used in both cases.\textsuperscript{31}

The formation of a neutral oxygen vacancy in BaNbO\textsubscript{2}N and LaNbON\textsubscript{2} can be expressed in Kröger–Vink notation as,

\[
\begin{align*}
O^\times + 2M^\times & \rightarrow 2M^\prime + V_O^{\bullet\bullet} + \frac{1}{2}O_2 \\
N^\times + 3M^\times & \rightarrow 3M^\prime + V_N^{\bullet\bullet} + \frac{1}{2}N_2
\end{align*}
\]

(1) and for a neutral nitrogen vacancy,

(2)

The oxidation state of the M cations in the vicinity of the defect will be determined by the localization of the electron density, which may vary between 2M\textsuperscript{′} + V\textsuperscript{\textbullet\bullet}O\textsuperscript{2−} and 2M\textsuperscript{′} + V\textsuperscript{\textbullet\bullet}N\textsuperscript{3−} for

Fig. 1 Anion ordering in M-O\textsubscript{2}N and M-O\textsubscript{2}Na octahedra.

Fig. 2 Unit cells of (a) P\textsubscript{n}m\textsubscript{a} BaNbO\textsubscript{2}N and (b) P\textsubscript{n}m\textsubscript{a} LaNbON\textsubscript{2}.
a neutral oxygen vacancy, and $3M^+ + V_N^{**}$ and $3M + V_N^*$ for a neutral nitrogen vacancy. As Nb is capable of exhibiting a range of oxidation states (+5 to 0), we reason that it will likely favour charged vacancies and reduced Nb cations in anion-deficient BaNbO$_2$N and LaNbON$_2$. To this end we investigate the effect of anion ordering effect on electron localization and Nb oxidation via a DDEC6 charge decomposition analysis.$^{32-34}$

For a neutral supercell, the anion vacancy formation energy, $E_{\text{f,vac}}$, can be obtained from the simplified expression: $^{35}$

$$E_{\text{f,vac}} = E_{\text{def}} - E_{\text{pris}} + \frac{1}{2} \mu_i$$

(3)

where $E_{\text{def}}$ is the defective supercell, $E_{\text{pris}}$ is pristine supercell and $\mu_i$ chemical potential for the missing anion. In this work we seek only to establish how anion ordering influences anion vacancy formation (and vice versa), and do not consider the additional effects induced by oxygen/nitrogen-rich synthesis conditions. To this end we only employ a single nitrogen and oxygen chemical potential, obtained from the fitted elemental-phase reference energies (FERE) ($\mu_O = -4.76$ eV and $\mu_N = -8.51$ eV).$^{36}$

Results and discussion

Anion ordering in Nb perovskite oxynitrides

BaNbO$_2$N. Fig. 3 illustrates each anion ordering considered here for BaNbO$_2$N. This anion ordering is defined in terms of $N^3-$–Nb$^{5+}$–$N^3-$ chains. The high symmetry of this structure ($P_{n3m}$ space group) enables an extensive search of anion orderings, including those that possess completely cis- or trans-ordered $N^3-$–Nb$^{5+}$–$N^3-$ chains, as well as those that possess a mixture of both cis- and trans-orderings. Fig. 4a depicts the relative energies of these distinct anion orderings, compared to the lowest energy structure of BaNbO$_2$N. The latter is the fully cis-C1 ordering, which has previously been found to be the most stable ordering in LaTiO$_2$N,$^{14}$ CaTaO$_2$N$^{17}$ and SrTaO$_2$N.$^{15}$ Fig. 4a shows that several fully cis-orderings considered here lie within 0.3 eV of C1, with the parallel ring structure C8 being the only exception. By comparison, local structures with fully trans-orderings (T1 and T2) are $>2$ eV less stable than the C1 ordering. Of these, the lowest energy fully trans configuration is T2, a 2D ordering comprised of stacked orthogonal layers of trans-$N^3-$–Nb$^{5+}$–$N^3-$ chains. Interestingly, Fig. 4a shows that the partial trans-anion orderings considered here (Q and H, which denote quarter and half trans-orderings, respectively) are all significantly lower in energy than the fully trans-configurations. Indeed, several quarter trans-orderings, such as Q1 and Q4, are predicted to be within 0.2 eV of the lowest energy C1 ordering. This suggests that distortion caused by trans-chains can be stabilized to a point by adjacent cis-chains. These results suggest that stabilizing the formation of a fully trans-ordered phase in BaNbO$_2$N will be significantly more challenging than conversion from cis- to partially/fully trans-ordered phases, or forming mixed-phases comprising both cis- and trans-ordered regions. Of the ring & loop configurations considered here (i.e. C7, C8, C9, Q2, H2),

![Fig. 3 N^3-Nb^{5+}-N^3- anion orderings in a 2 x 2 x 2 BaNbO_2N supercell (Ba^{2+} and O^{2-} atoms not shown for clarity). N^3- and Nb^{5+} are dark and light blue atoms, respectively.](image-url)
Fig. 4a indicates that these orderings generally have higher unfavourable strain is produced when the $N_3$–Nb$^{5+}$–$N_3$– chains ‘loop back’ upon themselves too tightly.

Fig. 4 also considers the relative stability of anion orderings in BaNbO$_2$N from the point of view of dimensionality, by highlighting which orderings are 2D and which are 3D. In general, cis-orderings are considered to be 2D, in that they consist predominantly of $N_3$–Nb$^{5+}$–$N_3$– chains aligned parallel with each other. Introducing locally trans-ordered $N_3$–Nb$^{5+}$–$N_3$– chains, either partially (Q configurations) or completely (T configurations) naturally increases the dimensionality of the ordering when ‘twists’ and ‘loops’ are present in the $N_3$–Nb$^{5+}$–$N_3$– sublattice (see Fig. 3). Nevertheless, Fig. 4a shows that there is no clear relationship between dimensionality and stability here. For instance, the 2D fully cis-ordered structures are lowest in energy (e.g. C1, C2, C3) whereas the 2D half-trans-ordered structures (H1, H2, H3, H4) are less stable by up to $\sim 1.2$ eV. Similarly, of the 3D orderings studied, the fully cis-C7, C10 and C11 and the quarter trans-Q1 and Q4 orderings have mostly very similar energies. Notably, the C10, Q1 and Q4 orderings are only $\sim 0.13$ eV higher in energy than the most stable C1 configuration. On the other hand, the dimensionality of the ordering has a clear relationship with the degree of lattice anisotropy, measured here via the deviation of each lattice constant from its value for a pristine P$n_{3n0}$ unit cell for each ordering (i.e. we define this value as the average of the $a$, $b$ and $c$ lattice constants in each case). Fig. 4b and c show that the 2D orderings considered here clearly induce greater anisotropy in the crystal lattice compared to 3D orderings, as anticipated. Indeed, lattice constant deviations correlate with the predominant alignment of $N_3$–Nb$^{5+}$–$N_3$– chains in the $2 \times 2 \times 2$ supercell. For instance, for the most stable C1 ordering, the $N_3$–Nb$^{5+}$–$N_3$– chains are aligned along the $a$ and $c$ lattice vectors (Fig. 3). This alignment causes equivalent expansion in $a$ and $c$ of $\sim 0.03$ Å, while the lattice is compressed in $b$ approximately twofold, by $\sim 0.07$ Å (Fig. 4b). On the other hand, C7 yields an essentially isotropic $P_{nmm}$ structure, and Fig. 3 shows that alignment of the $N_3$–Nb$^{5+}$–$N_3$– chains are balanced exactly in all three directions. These results suggest that inducing lattice strain in BaNbO$_2$N will yield selectivity over anion ordering which is in line with recent studies for other oxynitride perovskites.16,21,22 We return to a discussion of how these orderings influence thermokinetic parameters of vacancy defects below.

Beyond dimensionality, Fig. 4b and c show that these BaNbO$_2$N anion orderings fall into three distinct groups. The first of these comprise orderings that minimally distort the cubic symmetry of the ideal BaNbO$_2$N lattice, i.e. $a \approx b \approx c$. This isotropic group includes both high energy fully trans-orderings, as well as relatively stable C7 and Q2 orderings, and feature motifs in which $N_3$–Nb$^{5+}$–$N_3$– chains form a closed loop within a $2 \times 2 \times 2$ extension of the BaNbO$_2$N lattice. The second group consists of orderings that yield anisotropic compression/expansion in a single dimension (i.e. two lattice constants essentially equal but distinct from the third), such as C1, C2, C3, H1, H3, and H4. The third group are those orderings that yield complete anisotropy in the sense that all three BaNbO$_2$N lattice constants are unique (e.g. C3, C4 Q3, Q4, Q5). In the second group, the C1, C2 & C3 orderings (the three most stable orderings overall) are compressed in one axis and expanded in the other two. Interestingly, the half trans-orderings in this group (H1, H3, H4) all show the opposite trend, i.e. compression along two axes, and expansion in the third. These results suggest that cis-orderings in perovskite oxynitrides may be stabilised generally via in-plane lattice expansion, while trans-ordering may be stabilised via in-plane lattice compression. Indeed, Oka et al.21 demonstrated the formation of a metastable trans-type anion orderings in CaTaO$_2$N via Sr$^{2+}$ A-site doping, in which $N_3$–preferentially resided in axial sites in TaO$_2$O$_2$ octahedra due to lattice strain induced by the A-site dopant. Similarly, Vonruti et al.22 predicted the stabilization of parallel trans-ordering of $N_3$– anions (akin to T2) in LaTiO$_2$N when in-plane compressive strains greater than 4% were applied to the lattice. While an exhaustive strain engineering study is beyond the
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scope of this work, results presented here indicate that intermediate partial trans-orderings potentially impede the stabilization of fully trans-orderings via compressive in-plane strain, and so are likely an important consideration in strain engineering of perovskite oxynitrides more generally.

**LaNbON₂**. Fig. 5a illustrates the anion orderings considered here for LaNbON₂. Here NbO₂N₄ octahedra mean that anion ordering is best examined via O²⁻–Nb⁵⁺–O²⁻ chains, as opposed to N³⁻–Nb⁵⁺–N³⁻ chains. The lower orthorhombic symmetry here prevents an exhaustive study of anion orderings such as that presented above for the cubic BaNbO₄N. Here we consider a set of chain structures that can provide an adequate representation of fully cis- or fully trans-anion orders in LaNbON₂, and are commensurate with representation anion order sets considered in other DFT studies.¹⁵,¹⁷,²² Due to the lower symmetry of LaNbON₂, we have also considered the chains in perpendicular orientations. The total orderings considered was ultimately limited to those configurations that could be constructed in the unit cell and subsequently extended into the 2 × 1 × 2 supercell. Partial trans-orderings (akin to the Q and H structures considered for BaNbO₄N) are not possible in the orthorhombic LaNbON₂ unit cell without violating the NbO₂N₄ octahedra selection rule, and so have not been considered.

Fig. 5b displays the relative energies of the different anion orderings for the 2 × 1 × 2 LaNbON₂ cell. It is clear that cis-orderings are preferred over trans-orderings, consistent with results for BaNbO₄N presented in Fig. 4a. For LaNbON₂, all trans-orderings considered here (LT₁, LT₂ & LT₃) are > 2 eV less stable than the most stable cis-ordering, LC₉. The latter ordering features ‘zigzag’ O²⁻–Nb⁵⁺–O²⁻ chains running through the 2 × 1 × 2 supercell alternating between the (101) and (010) planes and perpendicular to the (011) and (011) directions. This zigzag motif is shared with the other stable anion orderings, LC₁, LC₂, and LC₁₀, the only difference being the alignment of the motif within the crystal structure. For instance, in the LC₁₀ ordering, the same zigzag O²⁻–Nb⁵⁺–O²⁻ chains are present in the 2 × 1 × 2 supercell as those observed in the LC₉ ordering. However, they are perpendicular to the (110) and (110) lattice directions, and as a result are ~0.2 eV higher in energy. Similarly, the LC₁ and LC₂ orderings also feature the zigzag O²⁻–Nb⁵⁺–O²⁻ chain motif, but perpendicular to the (101) and (010) lattice directions, respectively. Both orderings are only ~0.15 eV less stable than the most favourable ordering, LC₉. The other cis-orderings considered here consist of different structural motifs and are less stable than the zigzag motif. These include the LC₃, LC₄, LC₅ and LC₆ orderings, all of which consist of O²⁻–Nb⁵⁺–O²⁻ chains that create a repeating square-tooth pattern in the 2 × 1 × 2 LaNbON₂ supercell and are ~0.3–0.6 eV less stable than LC₉, and the ring-like LC₇ and LC₈ motifs, which are both ~0.5 eV less stable than LC₉.

Fig. 5b shows that the dimensionality of the ordering is also apparently unrelated to its stability. For instance, LC₉ and LC₁₀ are both 3D orderings, whereas all their cis-orderings of O²⁻–Nb⁵⁺–O²⁻ chains in LaNbON₂ are 2D. This is different from what was found in Fig. 4 for BaNbO₄N, and suggests that controlling for 2D or 3D more ordering may not be possible.

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**Fig. 5** (a) Representative O²⁻–Nb⁵⁺–O²⁻ anion orderings in a 2 × 1 × 2 LaNbON₂ supercell (La³⁺ and N³⁻ not shown for clarity). O²⁻ and Nb⁵⁺ are red and light blue atoms, respectively. (b) PBEsol energies of LaNbON₂ anion orderings shown in (a), relative to the lowest energy ordering LC₉.
in LaNbON2. Though we note that 2D–3D ordering transition temperatures have been observed in the comparable structure LaTaON2.20

Further, comparison of Fig. 5b with equivalent results for BaNbO3N (Fig. 3 and 4a), shows striking similarities between the relative stabilities of comparable O2––Nb5+–O2– orderings in LaNbON2 and N3––Nb5+–N3– orderings in BaNbO3N. For instance, cis-orderings featuring zigzag chain motifs are the most stable in both materials, and fully trans-anion orderings are significantly higher in energy (by ~1 eV). Further, the ring-like and loop-like motifs are also energetically similar in both cases. For instance, LC3, LC4, LC5 and LC6 in LaNbON2 and C4, C5 and C6 in BaNbO3N both feature repeating square tooth O2––Nb5+–O2– and N3––Nb5+–N3– motifs and have comparable relative energies (~0.3–0.4 eV). Similarly, the loop motifs in LC7 and LC8 for LaNbON2 and C8 and C9 in BaNbO3N are structurally similar and ~0.5–0.6 eV higher in energy than the most favourable ordering.

Nevertheless, the La3+ and Ba2+ A-site cations also drive secondary ordering effects that differ between BaNbO3N and LaNbON2. Comparing the La-O(N)12 coordination spheres between different orderings for LaNbON2, the lowest energy orderings (LC1–LC4 and LC9–10) all possess stoichiometric La-O6N6 coordination spheres, whereas the LC5–LC8 orderings feature a mix of La-O8N6 and La-O2N10 coordination spheres. This mix creates alternating LaO and LaN layers between NbON3– sheets aligned perpendicular to the b-axis in the 2 × 1 × 2 LaNbON2 supercell. There is a clear energetic difference between these two groups, with LC5–LC8 being ~0.3 eV higher on average than LC1–LC4 and LC9–10. This A-site effect is notably absent in the BaNbO3N orderings, shown in Fig. 4. While the most stable zigzag orderings in BaNbO3N do indeed create an even distribution of Ba-O8N4 coordination spheres, other orderings like C6 & C8 have energies 0.15–0.30 eV higher than orderings with comparable Ba-(O,N)12 coordination sphere distributions. Thus, the N3––Nb5+–N3– chain ordering in the more densely packed BaNbO3N supercell effectively masks the effect of the Ba-(O,N)12 coordination sphere on the stability of the material.

Vacancy defect formation energies in Nb perovskite oxynitrides

We now consider the impact of anion order in BaNbO3N and LaNbON2 on the stability of vacancy defects in both O2– and N3– lattice positions. This is achieved via predicting the vacancy defect formation energies, £V,N and £V,N (eqn (3)) at the 12 distinct anion positions in the respective supercells of these materials, for each specific anion ordering considered in the preceding discussion. These distinct positions 1–12 for the 2 × 2 × 2 BaNbO3N and 2 × 1 × 2 LaNbON2 supercells are depicted in Fig. 6a and b.

BaNbO3N. £V,N and £V,N in BaNbO3N for the 22 individual anion orderings introduced previously are shown in Fig. 6c, and grouped according to their cis-/trans-character. This figure shows that nitrogen vacancy defects in BaNbO3N have a smaller variation in formation energies in the presence of fully cis- (2.24–2.50 eV) or fully trans-ordering (1.14–1.46 eV). By contrast, the range of £V,N formation energies found for the quarter and half trans anion orderings (i.e. Q1–Q5 and H1–H4) is larger, 1.35–2.77 eV, presumably due to the greater structural anisotropy in these orderings, which gives rise to a greater number of distinct vacancy sites. Fig. 6c also shows that V,N sites in local cis- or local trans-anion sites of the partial trans-orderings are ~0.2 eV higher in energy than if the whole ordering was cis or trans.

The £V,N formation energies vary quite significantly across the fully cis- (4.87–6.08 eV) and partial trans- (4.87–5.98 eV) orderings, compared to fully trans- (5.37–5.60 eV). This indicating that

![Image](image-url)
neutral oxygen vacancy formation energies are more sensitive to \( \text{N}^{2-} - \text{Nb}^{5+} - \text{N}^{3-} \) chain disorder, whereas nitrogen vacancy formation energies depend simply on whether the site is in a \textit{cis}- or \textit{trans}-chain. \( \text{N}^{3-} \) anions in \textit{trans}-\( \text{N}^{2-} - \text{Nb}^{5+} - \text{N}^{3-} \) chains, whether they be partially or fully \textit{trans}, have a reduced \( E_{i,VN} \) formation energy.

The question as to whether anion vacancies have the potential to affect local anion order in BaNbO\(_2\)N is considered in Fig. S1 (ESI†), which shows the relative energies of these anion orderings in the presence of \( V_O \) and \( V_N \) defects. Compared to the defect-free relative energies in Fig. 4a, it can be seen in Fig. S1a (ESI†) that in several cases anion vacancies likely influence the anion ordering. For instance, the quarter-\textit{trans} orderings (Q1–5) become energetically indistinguishable from the \textit{cis} (C1–11) orderings in the presence of a neutral oxygen vacancy defect. Additionally, the relative orderings in the presence of a neutral nitrogen vacancy defect (Fig. S1b, ESI†) are significantly different from the defect-free orderings. While the \textit{cis} C1–11 orderings are effectively equivalent in energy with and without a \( V_N \) defect, the Q1–5 orderings are lowered by \( \sim 0.5 \text{ eV} \), as the defect disrupts an \( \text{N}^{3-} - \text{Nb}^{5+} - \text{N}^{3-} \) chain, thus making them the most favourable ordering.

\( \text{LaNbON}_2 \). \( E_{i,VN} \) and \( E_{i,VN} \) in LaNbON\(_2\) for the 12 individual anion orderings introduced previously are shown in Fig. 6d, and grouped according to their \textit{cis}-\textit{trans}-character. It is clear from this figure that \( \text{N}^{2-} \) anion vacancies form more easily in fully \textit{trans}-ordered structures (LT1, LT2, LT3) than the \textit{cis}-ordered LC structures. The LC5, LC6, LC7, and LC8 orderings are exceptions here, exhibiting \( E_{i,VN} \) values between only 4.82–5.54 eV (the lowest values for all orderings considered here). We note that these are the orderings that yield alternating LaO/LaN layers in LaNbON\(_2\). \( E_{i,VN} \) values are notably higher than \( E_{i,VN} \) for the LC orderings. This means that LaNbON\(_2\) domains rich in these more stable \textit{cis}-anion orderings are more likely to exhibit \( \text{O}^{2-} \) anion vacancies than \( \text{N}^{3-} \) vacancies. The same trend was noted above in our discussion of BaNbO\(_2\)N vacancy defects, indicating that the relative stabilities of \( \text{O}^{2-} \) and \( \text{N}^{3-} \) point vacancy defects in AMO\(_2\)N & AMON\(_2\) perovskite oxynitrides are potentially independent of the A-site cation and crystal symmetry. \( E_{i,VN} \) formation energies predicted for LaNbON\(_2\) (1.74 eV range) here are more sensitive to the local anion ordering, and thus exhibit a wider range than observed for BaNbO\(_2\)N (1.36 eV range). This is attributed to \( \text{N}^{3-} \) being the majority anion LaNbON\(_2\).

Finally, we consider whether or not \( V_O \) and \( V_N \) defects in LaNbON\(_2\) have the potential to influence the relative stabilities of these anion orderings. Fig. S2 (ESI†) shows the relative energies of the anion orderings in the defective LaNbON\(_2\) structures. Compared to the defect-free relative energies in Fig. 5a and Fig. S2a (ESI†) the presence of \( V_O \) does not appreciably influence the relative stability of many of the orderings. However, the LC5–9 orderings become the most stable orderings, as they can be lowered by up to \( \sim 0.2 \text{ eV} \). Fig. S2b (ESI†) shows that, by comparison, \( V_N \) defects are much more influential on the stabilities of these anion orderings, with all LC orderings being lowered by up to \( \sim 0.5 \text{ eV} \). Nevertheless, the relative stabilities for all LC orderings become virtually indistinguishable in the presence of a \( V_N \) defect.

**Vacancy defects and charge redistribution**

Nb is capable of exhibiting multiple low oxidation states. While our calculations enforce charge neutrality on the entire supercell, the region surrounding a vacancy defect is itself not necessarily guaranteed to be charge neutral due to electron density delocalisation. In turn, the oxidation states of Nb cations are not necessarily uniform throughout the supercell, since, despite the formal vacancy charge (i.e. \( V_O^{2-} \) and \( V_N^{3-} \)) electron density delocalisation around the vacancy may lead to charge redistribution on neighbouring atoms. We examine this possibility in BaNbO\(_2\)N and LaNbON\(_2\) via the DDEC6 charge decomposition analysis presented in Table 1, which summarizes the partial atomic charges and charge redistribution in these materials following the formation of \( V_O \) and \( V_N \) defects. We limit our discussion to only the most thermodynamically stable \textit{cis}/\textit{trans} anion orderings for each material, established in the preceding discussion (i.e. C1 and T2 in BaNbO\(_2\)N, and LC9 and LT2 for LaNbON\(_2\)). Due to the size of the supercells used in this work, we have not verified these PBEsol results with higher-level exchange correlation functionals, such as HSE06.\(^{36,37}\) We point out, however, that charges based on PBEsol have been shown to be in close agreement with higher level functionals for closely related transition metal oxide perovskites.\(^{38,39}\)

For BaNbO\(_2\)N, Table 1 shows that charge redistribution, due to delocalisation of the electron density around the defect site, leads to the ‘true’ charge of \( V_O^{2+} \) and \( V_N^{3+} \) defects being only

| BaNbO\(_2\)N | LaNbON\(_2\) |
|---|---|
| **Partial Charge** | **Partial Charge** |
| Adjacent Nb | 1.89 | 1.79 |
| Other Nb | 2.21 | 2.20 |
| **Charge Redistribution** | **Charge Redistribution** |
| Ba/La | \(-0.23\) | \(-0.27\) |
| Nb | \(-1.26\) | \(-0.79\) |
| Total | \(-1.51\) | \(-1.06\) |
LT2 and LC9 structures exhibit essentially equivalent average Nb partial charges (2.14 compared to 2.10, not shown in Table 1), the introduction of the VO defect disrupts a trans-O2\(^{-}\)--Nb5+-O2\(^{-}\) chain in the LT2 structure, but leaves the chain in the cis LC9 ordering unperturbed. This reduces the Nb sublattice by \(-1.71\) e more in LT2, compared to LC9 ordering (\(-1.06\) e).

Vacancy diffusion barriers in Nb perovskite oxynitrides

With the thermochemical stability of V\(^{\text{trans}}\)\(_{\text{N}}\) and V\(^{\text{cis}}\)\(_{\text{O}}\) vacancy defects in BaNbO\(_{2}\)N and LaNbON\(_{2}\) now established, we conclude our discussion by considering the impact of anion ordering on vacancy diffusion kinetics in these materials. Fig. 7 presents diffusion pathways of V\(^{\text{trans}}\)\(_{\text{N}}\) and V\(^{\text{cis}}\)\(_{\text{O}}\) vacancy defects in BaNbO\(_{2}\)N and LaNbON\(_{2}\) elucidated using the CI-NEB method. Due to the expense of this approach, we consider defect diffusion in only the most stable cis- and trans-anion orderings (i.e. the most relevant), and only those diffusion pathways corresponding to vacancies moving between adjacent positions in the crystal lattice (i.e. the distinct positions defined in Fig. 6a and b). For BaNbO\(_{2}\)N we assess the accuracy of diffusion barriers obtained with the 2 \times 2 \times 2 supercell by comparing them with barriers obtained with a 3 \times 3 \times 3 supercell in Fig. S3 and Table S3 (ESI†). This comparison indicates that shorter diffusion pathways (rotation about a Nb ion) are significantly less sensitive to supercell size than longer pathways (shifting to other Nb ion coordination spheres), as anticipated. Importantly, Table S3 (ESI†) indicates that the trends in vacancy diffusion barriers found using the 2 \times 2 \times 2 supercell are reproduced with the 3 \times 3 \times 3 supercell. The longer diffusion pathways in LaNbON\(_{2}\) are orientated to the a/c plane in the 2 \times 1 \times 2 orthorhombic supercell, and so it is likely they are already converged with respect to the a/c dimensions of the supercell.

**Fig. 7**  V\(^{\text{cis}}\)\(_{\text{N}}\) & V\(^{\text{trans}}\)\(_{\text{O}}\) diffusion pathways and associated PBEsol diffusion barriers (eV) for the most stable cis- and trans-anion orderings in (a and b) BaNbO\(_{2}\)N and (c and d) LaNbON\(_{2}\). (a) BaNbO\(_{2}\)N, C1 ordering, (b) BaNbO\(_{2}\)N, T2 ordering, (c) LaNbON\(_{2}\), LC9 ordering, (d) LaNbON\(_{2}\), LT1 ordering. All diffusion pathways were calculated in the complete 3 \times 3 \times 3 and 2 \times 1 \times 2 supercells, respectively, however only the core region is depicted here for clarity. Anion positions are defined in Fig. 5a and b for BaNbO\(_{2}\)N and LaNbON\(_{2}\), respectively.
**BaNbO$_2$N.** Diffusion pathways for $V^{'*}$_N and $V^{'*}_O$ vacancies in the most stable C1 and T2 orderings of BaNbO$_2$N and the corresponding energy barriers are presented in Fig. 7a and b. There are two distinct pathways for each vacancy type; the defect can rotate positions about a Nb$^{5+}$ cation (O1 $\rightarrow$ O2, N7 $\rightarrow$ N12 in C1 (Fig. 7a); O5 $\rightarrow$ O2 in T2 (Fig. 7b)) or the defect can migrate to a non-adjacent position, shifting to a different Ta$^{5+}$ cation but rotating about the Ba$^{2+}$ cation (O1 can migrate to a non-adjacent position, shifting to a different O2). The latter of these pathways is obviously the longest and so is anticipated to correlate with the highest diffusion barrier. Fig. 7a and b show that this is the case; $V^{'*}_O$ and $V^{'*}_N$ migration between non-adjacent sites is impeded by barriers ranging from 5.33 eV to 6.70 eV while rotation of the defect to adjacent positions around the Nb$^{5+}$ cation corresponds to a barrier of only 1.13 eV to 1.53 eV. Fig. 7a and b also shows that, in general, $V^{'*}_O$ diffusion are barriers around ~25% lower than the analogous diffusion pathways for $V^{'*}_N$. $V^{'*}_N$ diffusion in the less stable T2 ordering is further impeded by the fact that it can only occur between adjacent NbO$_2$N$_4$ octahedra, and not via rotation around an individual Nb$^{5+}$ cation, which would correspond to a lower barrier. Thus, despite being more stable in BaNbO$_2$N, O$^{2-}$-vacancy defects are expected to undergo more facile diffusion, most notably in trans-ordered phases, impeding control over long range ordering in this material. We note also that these findings are consistent with our recent study of TaON, in which it was shown that diffusion barriers for $V^{'*}_N$ migration are potentially low enough to displace nitrogen content from the oxynitride. Thus, it is suggested that stabilising trans-ordered phases of BaNbO$_2$N is likely to yield more effective retention of nitrogen content in this material, even if long-range order cannot be controlled.

**LaNbON$_2$.** Diffusion pathways for $V^{'*}$_N and $V^{'*}_O$ vacancies in the lowest energy cis- and trans-ordered structures of LaNbON$_2$, LC9, and LT1, and the corresponding energy barriers are presented in Fig. 7c and d. In the LC9 cis-ordering, Fig. 7c, O$^{2-}$ vacancies can only diffuse via the O10 $\rightarrow$ O12 pathway, while N$^{3-}$ vacancies have two possibilities for migration via rotation around a Nb$^{5+}$ cation (N6 $\rightarrow$ N3) and between non-adjacent (N6 $\rightarrow$ N7) sites that cross the cavity between La$^{3+}$ ions. In the latter case the defect is shifting to a separate NbO$_2$N$_4$ octahedron while rotating is coordinating about the local La-(O,N)$_{12}$ coordinate sphere. In the less stable LT1 trans-ordering, Fig. 7d, again O$^{2-}$ vacancies can only migrate via a single long pathway (O6 $\rightarrow$ O7) since rotation about an individual Nb$^{5+}$ cation to another O$^{2-}$ site isn’t possible, whereas N$^{3-}$ vacancies can migrate via the N12 $\rightarrow$ N10 pathway and along the longer non-adjacent N10 $\rightarrow$ N3 pathway. Consistent with BaNbO$_2$N, the $V^{'*}_O$ diffusion barriers are seen to be sensitive to whether the diffusion path is between adjacent anion positions or non-adjacent positions with O10 $\rightarrow$ O12 in LC9 predicted to have a barrier height of 0.71 eV, while O6 $\rightarrow$ O7 in LT2 is 3.12 eV. However, the difference in the $V^{'*}_N$ diffusion barriers for adjacent and non-adjacent paths is greatly reduced compared to BaNbO$_2$N. In LC9 the adjacent pathway height is 1.56 eV with the non-adjacent path barrier only 0.29 eV higher, while in LT2 the adjacent $V^{'*}_N$ diffusion is now 0.72, with the non-adjacent barrier merely 0.82 eV. Interestingly, the kinetic stability of N$^{3-}$ vacancy defects in LaNbON$_2$ is significantly reduced from that observed in BaNbO$_2$N. In particular, in the less stable LT1 trans-ordering, N$^{3-}$ vacancies diffuse more easily than O$^{2-}$ vacancies. The origin of this reduction is a cooperative effect in which the migrating $V^{'*}_N$ vacancy partially displaces an adjacent O$^{2-}$ anion. The additional space created by this displacement gives rise to an asymmetric path, in which the $V^{'*}_N$ vacancy does not pass directly between adjacent La$^{3+}$ cations along the diffusion pathway. In doing so, the migrating $V^{'*}_N$ vacancy partially displaces an adjacent O$^{2-}$ anion and so reduces the diffusion barrier.

**Conclusions**

The impact of anion ordering on defect engineering in perovskite oxynitride photocatalysts remains largely unexplored, despite it being the necessary first step towards controlling defects in these materials for improved photocatalytic performance. Using accurate first-principles calculations, we have presented an extensive investigation of cis- and trans-anion orderings in two exemplar perovskite oxynitrides, BaNbO$_2$N and LaNbON$_2$, and examined how these orderings influence (1) overall stability, (2) the stability of N$^{3-}$ and O$^{2-}$ point defects and (3) the mobility of these defects through the bulk material. Analysis of partial charges with DDEC6 confirmed that the anion ordering influenced the degree of e$^-$ redistribution to adjacent and outer Nb cations from the creation of an anion vacancy.

For BaNbO$_2$N, our results show clearly that fully cis-anion orderings are more stable than fully trans-anion orderings. The influence of these orderings on the cubic lattice vectors however demonstrates differing degrees of anisotropy. This ultimately has implications for strain engineering in this oxynitride; specifically, it may be difficult to stabilize the fully trans-orderings in BaNbO$_2$N, over half-trans or fully-cis orderings, via in-plane compression of the crystal lattice. In LaNbON$_2$, 2D & 3D orderings have comparable energies, meaning that mixed dimensionality in anion ordering may be more prevalent in this material. However, our results show the presence of a secondary ‘A-site coordination sphere effect’ influencing the stability of different orderings in LaNbON$_2$, where the stoichiometric distribution of O$^{2-}$ and N$^{3-}$ in La-(O,N)$_{12}$ gives rise to obvious differences in the relative energies of different fully cis-anion orderings. This effect is less obvious in BaNbO$_2$N, which we contend is due to the more densely packed lattice having a higher degree of symmetry, which masks any Ba-(O,N)$_{12}$ coordination sphere on the overall stability of the material. Vacancy defect formation energies for BaNbO$_2$N indicate that domains rich in cis-anion orderings (the most favourable) may preferentially stabilise O$^{2-}$ anion vacancies less uniformly in their structure, whereas N$^{3-}$ anion vacancies are less likely. On the other hand, O$^{2-}$ defect formation energies in LaNbON$_2$ are more sensitive to the local anion ordering, than its overall cis- or trans-character. This is attributed to the effect of the La$^{3+}$ A-site cation, which for particular orderings considered here gives rise to alternating layers of LaO and LaN that reduce significantly O$^{2-}$ vacancy defect formation energy.
For BaNbO$_2$N, $V_{O}^{**}$ diffusion barriers were found to be lower than $V_{Nb}^{**}$, most notably in trans-ordered phases. It is predicted that this will impede control over long range ordering in BaNbO$_2$N. Stabilising trans-ordered phases of this material is thus predicted to yield more effective retention of nitrogen content in its structure, irrespective of long-range anion order. In this sense, BaNbO$_2$N bears some resemblance to TaON, for which $V_{O}^{**}$ migration barriers are potentially low enough to displace nitrogen content from the oxynitride.\(^4\) The reverse is observed true for $V_{Nb}^{**}$ in LnNbO$_3$, i.e. N$^{3-}$ vacancy defects exhibit lower diffusion barriers than O$^{2-}$ vacancy defects. $V_{O}$ diffusion via both adjacent and non-adjacent pathways in LnNbO$_3$ benefits from the lower orthorhombic symmetry. In part this is due to the disruption the migrating N$^{3-}$ defect has on the local coordination environment; when rotating around a local La$^{3+}$ cation the N$^{3-}$ anion vacancy partially displaces an adjacent O$^{2-}$ ion to lower the diffusion barrier.

Conflicts of interest

There are no conflicts to declare.

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