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# A computational approach for epitaxial polymorph stabilization through substrate selection

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## Abstract

With the ultimate goal of finding new polymorphs through targeted synthesis conditions and techniques, we outline a computational framework to select optimal substrates for epitaxial growth using first principle calculations of formation energies, elastic strain energy and topological information. To demonstrate the approach, we study the stabilization of metastable VO<sub>2</sub> compounds which provides a rich chemical as well as structural polymorph space. We find that common polymorph statistics, lattice matching and energy above hull considerations recommends homostructural growth on TiO<sub>2</sub> substrates, where the VO<sub>2</sub> brookite phase would be preferentially grown on the  $a - c$  TiO<sub>2</sub> brookite plane while the columbite and anatase structures favor the  $a - b$

plane on the respective  $\text{TiO}_2$  phases. Overall, we find that a model which incorporates a geometric unit cell area matching between the substrate and the target film as well as the resulting strain energy density of the film provide qualitative agreement with experimental observations for the heterostructural growth of known  $\text{VO}_2$  polymorphs: rutile A- and B phases. The minimal interfacial geometry matching and estimated strain energy criteria provide several suggestions for substrates and substrate-film orientations for the heterostructural growth of the hitherto hypothetical anatase, brookite and columbite polymorphs. These criteria serve as a preliminary guidance for the experimental efforts stabilizing new materials and/or polymorphs through epitaxy. The current screening algorithm is being integrated within the Materials Project online framework and data and hence publicly available.

## Keywords

epitaxy, substrate selection, topology, elastic energy, homoepitaxy, heteroepitaxy

## 1 Introduction

Discovery and synthesis of new functional materials is essential in materials research to enable breakthrough technologies in energy storage, delivery and utilization. While computational approaches to predicting novel materials are becoming increasingly popular,<sup>1</sup> the ability to theoretically predict the preferred synthesis conditions of a target new material is less routine. In this context, synthesis of highly textured or epitaxial films - the natural or artificial growth of crystals on a crystalline substrate - provides an ideal platform as it allows for many control variables such as substrate selection, temperature, interfacial chemistry, deposition rates, etc to favor a specific local minimum in the free-energy landscape<sup>2</sup> corresponding to the target material. Among the variable conditions for epitaxy, the substrate selection is particularly important as it can decrease the nucleation energy of a given target, specifically

metastable, phase which can exhibit dramatically different physical or chemical properties compared to the ground state.<sup>3</sup> This is beautifully illustrated by the recent 2014 Nobel Prize in Physics, which was awarded for the invention of efficient blue light-emitting diodes based on epitaxially stabilized cubic GaN on a (001)-GaAs substrate.<sup>4</sup> An extensive overview of the applications, physics and challenges in epitaxial growth, partially concerning transition-metal oxide hetero-interfaces can be found in Refs. [ 5,6].

Usually, an epitaxial substrate is manually selected from a pool of common candidates using visualization software to select an appropriate surface, a rough lattice parameter matching and intuition.<sup>7</sup>To broadly explore new functional polymorphs using epitaxy, a more systematic, efficient and rational screening methodology of substrates is desirable. Several recent experimental combinatorial efforts<sup>8,9</sup> highlight the need to correctly identify a suitable substrate as well as the experimental conditions for high-throughput epitaxial film growth. Computationally, Mehta et al.<sup>10</sup> used ionic substitution to evaluate polymorph metastability within several metal dioxide systems where, not surprisingly, the calculated formation energy of the target compound was found to be a guiding but inconclusive criteria to predict the resulting epitaxial phase. To include an approximate effect of the substrate, the bulk modulus of each polymorph was computed to construct a free energy substrate-film model to evaluate the accessibility of the target phase. It is worth noticing that the work by Mehta et al.<sup>10</sup> focused on which polymorph is accessible through epitaxial growth, but did not address the reverse question; given a particular target material/polymorph - what is the optimal substrate selection and resulting epitaxial orientation?

To facilitate the synthesis of novel functional metastable materials, the goal of this work is to propose and implement an efficient and general computational screening approach for substrate selection. Given a target chemical compound and/or polymorph, we envision a process where the method and criteria are specified, the pool of candidate substrates is selected (could be up to a hundred or more) and the list of best possible substrate matches as well as the corresponding orientation relationship with the target film is generated in

real-time.

The presented methodology is benchmarked for the specific case of VO<sub>2</sub> polymorph growth using available references in the literature. Polymorphism in vanadium dioxide VO<sub>2</sub> has long attracted significant interest particularly due to its metal-insulator transition which can manifest as a function of temperature, strain, applied electric field and defect chemistry.<sup>11-13</sup> At high temperatures, VO<sub>2</sub> presents a metallic rutile (R) structure, which - upon cooling past a critical temperature - undergoes a dimerization of the vanadium into a distorted semiconducting monoclinic structure (M1). Additionally, two other structures, the A- and B-phases, have been synthesized under hydrothermal and/or physical vapor deposition conditions,<sup>14,15</sup> while other structures such as anatase, brookite and columbite seen in TiO<sub>2</sub> have not yet been observed for VO<sub>2</sub>. Hence, we are especially interested in finding recommendations for growing these hitherto unseen VO<sub>2</sub> polymorphs.

Table 1: Calculated structures of TiO<sub>2</sub> and VO<sub>2</sub> polymorphs.

Structure	Space group	Oxide	Lattice Parameter (Å)		
			a	b	c
TiO <sub>2</sub> polymorphs					
Rutile	P4 <sub>2</sub> /mnm	TiO <sub>2</sub>	4.65	4.65	2.97
		VO <sub>2</sub>	4.51	4.51	3.03
Brookite	Pbca	TiO <sub>2</sub>	5.18	5.51	9.27
		VO <sub>2</sub>	5.21	5.41	9.19
Columbite	Pbcn	TiO <sub>2</sub>	4.59	4.94	5.58
		VO <sub>2</sub>	4.53	5.00	5.44
Anatase	I4 <sub>1</sub> /amd	TiO <sub>2</sub>	3.81	3.81	9.72
		VO <sub>2</sub>	3.90	3.90	9.17
VO <sub>2</sub> polymorphs					
A-Phase	P4/ncc (130)	VO <sub>2</sub>	8.57	8.57	3.85
B-Phase	C2/m (12)	VO <sub>2</sub> *	12.39	3.75	6.49

\*β = 106.8°

## 2 Methodology

### 2.1 Computational

We aim to provide a fast and efficient model to pre-select substrates from a given pool for epitaxial growth of a target polymorph/material. Here we investigate two different approaches and a variety of criteria associated with each. In the following we present analyses, benchmarking and recommendations for:

**homostructural epitaxy** where a chemically and structurally similar substrate material is selected based on common polymorph statistics, lattice matching and energy above the hull. In this model the optimal orientation relationship between the film and the substrate is chosen as the smallest lattice mismatch between the common structures.

**heterostructural epitaxy** where the pool of candidate substrates can generally comprise any chemical system and the orientation relationship between the film and the substrate is obtained through a set of criteria based on the minimal interfacial geometry matching and estimated strain energy as a function of the substrate-film pair.

Both models are explored and implemented within the infrastructure of the Materials Project and benchmarked using available literature references for the case of VO<sub>2</sub> polymorph stabilization. We emphasize that a detailed investigation of interfacial chemical interactions - while beyond this work, may be critical in some cases and can be performed using slab calculations as an added, albeit more time-consuming computational approach. For a comprehensive collection of candidate substrates, we used the Materials Project database<sup>16</sup> as an "a priori" calculated dataset to search representative structures and evaluate the corresponding polymorph thermodynamic stability. Density-functional-theory (DFT) calculations were performed as necessary using the projector augmented wave (PAW) method<sup>17,18</sup> as implemented in the Vienna *Ab Initio* Simulation Package (VASP)<sup>19,20</sup> within the Perdew-Burke-Enzerhof (PBE) Generalized Gradient Approximation (GGA) formulation of the exchange-correlation

functional.<sup>21</sup> A cut-off for the plane waves of 520 eV is used and a uniform k-point density of approximately 1,000 per reciprocal atom is employed. We note that the computational and convergence parameters were chosen consistently with the settings used in the Materials Project<sup>16,22</sup> to enable direct comparisons with the large set of available MP data.

### 3 Results and Discussion

To demonstrate the various ways computational guidance can be leveraged for selecting a suitable substrate for epitaxial growth, we first choose a target film system. Due to the extensive polymorphism, diverse chemistry and oxidation states of the vanadium oxides, as well as their potential interest for electronic applications, such as transparent conducting films, catalysts, ...<sup>23 24,25</sup> we find the family of VO<sub>2</sub> polymorphs well suited to focus and illustrate our analysis and substrate screening process. Previously epitaxially grown VO<sub>2</sub> polymorphs, available in the literature, are used as benchmarks for our models. For metastable VO<sub>2</sub> polymorphs that have yet to be observed/successfully synthesized - and which could have interesting properties - substrate recommendations for future epitaxial growth are made.

#### 3.1 Homostructural Epitaxy

The easiest way to use available computational resources to select a potential substrate is to use chemical and structural similarity as a guide to homostructural growth. Essentially, if one wants to grow a new metastable polymorph, a naive guess for a substrate would be a material with the same structure, low lattice mismatch and similar chemistry. To generally explore this concept and exemplify it for our chosen VO<sub>2</sub> system, we perform simple data statistics of common polymorphism within the binary oxides. For all MO<sub>x</sub> oxide structures available in the Materials Project, Figure 1 illustrates the number of similar oxide structures found within 100 meV/atom of the ground state hull<sup>26</sup> for each pair of metal elements. We hypothesize that a large number of identical (within a given structural similarity tolerance) metastable

structures close to the ground state hull correlates with chemical similarity between the systems. This speculation is corroborated by high numbers for intuitively similar elements such as Ti-V, Mn-V, Mn-Fe, Mn-Co, Mn-Ni, Co-Fe and Zr-Ti, which all exhibit more than five similar polymorph structures within the given energy range. The binary titanium oxides show an exceptionally high degree of common polymorphism with  $\text{VO}_2$ , although we caution that this result may be somewhat skewed by the high degree of interest in these systems (e.g. more structures reported and explored) due to their electronic and magnetic versatility as a function of small structural changes. Given the large number of similar structures common to the titanium and vanadium oxides, we select the  $\text{TiO}_2$  system as a basis for homostructural growth, as well as a good benchmark. In natural minerals,  $\text{TiO}_2$  has three well-known polymorphs, i.e. anatase, rutile and brookite. The columbite structure of  $\text{TiO}_2$  is also found in suevite from the Nördlinger Ries crater which was likely formed under impact-induced high-pressure conditions.

Using DFT, we computationally relaxed the aforementioned high-symmetry polymorphs of interest for  $\text{VO}_2$  and  $\text{TiO}_2$ ; rutile, A- and B phases (experimentally observed for  $\text{VO}_2$ ) as well as anatase, brookite and columbite (experimentally observed for  $\text{TiO}_2$  but not  $\text{VO}_2$ ). First, to obtain a sense of the accessible energy scale through various synthesis techniques we compare the calculated thermodynamic stability with available evidence of successful synthesis, for both  $\text{VO}_2$  and  $\text{TiO}_2$ . Figure 2 shows the relative bulk formation energies (at  $T = 0$ ) for the various  $\text{VO}_2$  structures and  $\text{TiO}_2$ . For  $\text{TiO}_2$ , PBE-DFT erroneously predicts anatase (-3.51 eV/atom) as the ground state at zero pressure. This is well within the standard DFT error on formation energies for oxides which is normally distributed with a mean of zero and a standard deviation of 25 meV/atom.<sup>27</sup> The other three naturally occurring  $\text{TiO}_2$  polymorphs, i.e. rutile, brookite and columbite, are close in energy, about 15-30 meV/atom higher than anatase. These results are consistent with previous examinations of the  $\text{TiO}_2$  system.<sup>28</sup> We now turn to the  $\text{VO}_2$  family of polymorphs. Due to the strong lattice correspondence between the rutile and M1 phase and the small lattice expansion



observed (1%),<sup>29</sup> we will in this work consider them as one system, referred to as the "R/M" phase. Among the polymorphs considered for the VO<sub>2</sub> system, the R/M phase exhibits the lowest formation energy (-2.48 eV/atom). Brookite and columbite VO<sub>2</sub> have comparable formation energies, which are about 20 meV/atom higher than that of the R/M phase, whereas anatase has a higher relative energy (about 60 meV/atom). These results are also consistent with previous studies, which assessed the VO<sub>2</sub> formation energies in different prototype structures<sup>10</sup> for a range of different functionals.<sup>30,31</sup> To further evaluate the correlation between accessibility (e.g. successful synthesis) and the calculated zero Kelvin energy difference, we also present the results of the A- and B-phases. Our calculations shows that the B-phase is similar in energy to the brookite and columbite structures, while the energy of the A-phase is higher than all other structures considered here (about 80meV/atom higher than the rutile structure). Comparing the energy range of the polymorph space with evidence of successful synthesis (at some conditions) provides us with a estimated 'accessible energy' scale. For example, we note that the metastable A-phase has been successfully synthesized using hydrothermal<sup>14</sup> and physical vapor deposition techniques.<sup>32</sup> Hence, the present results indicate, rather encouragingly, that a large exploration energy window of metastability (up to 80 meV/atom including potential inaccuracies in DFT) may be overcome using customized synthesis techniques and conditions. Specifically, we note that any failure of DFT to obtain the correct ground state for either substrate and/or target system is of less importance in this work, as long as consideration is taken to include that error into the estimated accessible energy window and that the other criteria (lattice matching and chemical similarity) are applicable.

Secondly, the relaxed VO<sub>2</sub> crystal structures and lattice parameters are listed in Table 1, in comparison with TiO<sub>2</sub>. Not surprisingly, the lattice constants of the same TiO<sub>2</sub> and VO<sub>2</sub> prototype structures are very similar, where the largest relative difference ( $\Delta = 5.6\%$ ) is shown along the c-axis for the anatase structure. The small differences in lattice parameter between TiO<sub>2</sub> and VO<sub>2</sub> for the same prototype structure suggest new VO<sub>2</sub> polymorphs may

be achieved through homostructural VO<sub>2</sub> epitaxial growth on TiO<sub>2</sub>. Indeed, pseudomorphic growth work by Gao et al.<sup>35,36</sup> achieved a few atomic layers of anatase VO<sub>2</sub> on TiO<sub>2</sub> which is consistent with the an approximate critical layer thickness of 4 nm. Epitaxial growth typically requires a lattice mismatch between the substrate and film below 5% in lattice parameter.<sup>37</sup> From Table 1, we note that the *a* and *c* axes provide an interfacial preference between the VO<sub>2</sub> and TiO<sub>2</sub> brookite structures, while the *a* - *b* plane would be more favored for homostructural VO<sub>2</sub> growth on TiO<sub>2</sub> columbite and the anatase. We also compared the structural parameters of the A- and B-phases for VO<sub>2</sub> with experimental measurements and found agreement within 2%.<sup>15</sup>

Hence, for the stabilization of metastable VO<sub>2</sub> polymorphs, we find that common polymorph statistics, lattice matching and energy above hull considerations recommends homostructural growth on TiO<sub>2</sub> substrates. The VO<sub>2</sub> brookite phase would be preferentially grown on the TiO<sub>2</sub> brookite *a* - *c* plane and the VO<sub>2</sub> columbite and anatase phases favor growth on the TiO<sub>2</sub> *a* - *b* columbite and anatase planes, respectively.

### 3.2 Heterostructural Epitaxy

To build a more versatile substrate selection algorithm we have to go beyond the simple lattice parameter and chemical similarity matching between homomorphic (e.g. growing VO<sub>2</sub> anatase on TiO<sub>2</sub> anatase) structures. A general model would ideally allow us to look beyond common substrates for any orientation relationship between the substrate and the target film. A coherent interface between the substrate and target film implies a translational symmetry that is compatible with both surfaces. Zur and McGill<sup>38</sup> proposed a topological interface matching approach based on the minimization of the coincident area of matching 2D super-lattices from the various faces of the substrate and film lattices within a given strain constraint. This approach is an improvement from traditional lattice parameter matching, which is not applicable for systems where the epitaxial layer has a different orientation, or a completely different crystal structure, than the substrate. Additionally, while devoid of

any chemical interaction between the target film and substrate, the model provides a rapid geometrical and robust screening and we select it for implementation in pymatgen<sup>39</sup> (the open python-based analysis software adopted for MP) and dissemination within the Materials Project Design environment. In this process, we take advantage of existing surface modules as well as symmetry operations within pymatgen to generate all possible surface orientations of Miller index  $(hkl)$  below a certain cutoff and terminations.<sup>34,39</sup> The candidate substrates can be automatically selected from the Materials Project or generated from an external list. To accommodate a lattice match within the Zur and McGill model, the film is considered to be strained within the epitaxial plane. Hereafter, we will refer to this epitaxial plane as the  $x$ - $y$  plane. If we assume the substrate surface as rigid with no structural relaxation perpendicular to the  $x$ - $y$  plane, the strain energy ( $\Delta E_s$ ) imposed on the film can be expressed as  $\Delta E_s = V \cdot e^{x-y}$ , where  $V$  is the volume of the film per atom and  $e^{x-y}$  is the film strain energy density induced in the  $x$ - $y$  plane. Here, we adopt the recently developed elastic constant ( $C_{ijkl}$ ) high-throughput computation framework<sup>22</sup> within the Materials Project which allows for an easy estimate of  $e^{x-y}$  as:

$$e^{x-y} = V \cdot \frac{1}{2} C_{ijkl}^* \epsilon_{ij}^{x-y} \epsilon_{kl}^{x-y} \quad (1)$$

where  $C_{ijkl}^*$  is obtained by the transformation of the fourth-order tensor  $C_{ijkl}$  into the new lattice orientation correspondence between the substrate and the film. Through this procedure, we can preliminarily identify appropriate substrates and the lattice orientations that geometrically fit the target polymorph film as a function of the film strain energy. We note that there is a DFT error affecting the energy ordering of systems as previously witnessed in the formation energies for  $\text{VO}_2$  and  $\text{TiO}_2$ . The DFT evaluations of the elastic tensor are relatively accurate, within 15% of the experimental value<sup>22</sup> and will at worst contain a systematic error that should have a small effect in the overall ranking of different substrates for epitaxy.

Generally considering heteroepitaxy of metastable structures we note that the epitaxial constraint aims to overcome the difference in total energy (e.g. formation energy at  $p, T = 0$  + strain energy) for the target structure vs. all other polymorphs including the ground state. In the case of the  $\text{VO}_2$  system - the differences in free energy between different polymorphs are quite small, and for clarity as well as transparency of inherent DFT errors, we present and evaluate the strain energy and the geometric matching area as separate selection tools in choosing epitaxial substrates with optimal selectivity. However, we emphasize that the total energy change under epitaxial strain is straightforward to include in the current approach and an example is provided further down in the section. Following the Zur and McGill convention, for each pair of substrate and film, one value of minimal common unit cell area can be derived. While the substrate and its orientation can be selectively chosen under experimental conditions, films with different orientations that fall within the epitaxial geometrical limit are all feasible and will compete with one another. To imitate this competition, we consider the growth orientation that yields the lowest minimal common unit cell area and hence the least incoherent interface, for any particular film. Hereafter, we refer to the corresponding common unit cell area as the minimal coincident interface area (MCIA) and we estimate a 'small' MCIA criteria by taking 40 integers of a typical unit surface cell, e.g.  $\leq 400 \text{ \AA}^2$ . Using the two concepts of the geometric surface area matching as well as the film strain energy separately as selection criteria we evaluate the model on a set of substrate- $\text{VO}_2$  pairs for which experimental results are available in the literature. Figure 3 shows epitaxial lattice matching results with a maximal 3% strain for three known  $\text{VO}_2$  polymorphs (R/M, A and B-phase) on the following substrates:  $\text{SrTiO}_3$ ,  $\text{MgO}$ ,  $\text{LaAlO}_3$  and  $\text{Al}_2\text{O}_3$ , which have all been previously used for epitaxial growth of  $\text{VO}_2$ . Our calculations show that both R/M and A phases have small MCIA ( $\leq 150 \text{ \AA}^2$ ), with the corresponding  $\Delta E_s$  of 17 and 10 meV/atom, respectively. The B phase has a relatively large MCIA ( $290 \text{ \AA}^2$ ) while the corresponding  $\Delta E_s$  (2 meV/atom) is the lowest among the three polymorphs. Hence, considering both the geometric area as well as the strain energy, we find

no strong preference between the three polymorphs and would suggest that they could all be grown on a (100)-SrTiO<sub>3</sub> substrate. Indeed, Srivastava et al.<sup>32</sup> found that either R/M, A- or B- phase films can be grown epitaxially on a (100)-SrTiO<sub>3</sub> substrate through pulsed laser deposition and that the obtained phase selectivity depended on the oxygen pressure and laser frequency. Considering the next substrate (111)-MgO we find only large MCIA (495 and 449 Å<sup>2</sup>) for the A or B phases, respectively while the R/M phase yields relatively low values of MCIA (155 Å<sup>2</sup>) and strain energy  $\Delta E_s$  (3 meV/atom). This is again corroborated by available experiments; radio frequency sputtering techniques were utilized to deposit VO<sub>2</sub> on (111)-MgO and (111)-LaAlO<sub>3</sub> followed by annealing, which both present R/M structured epitaxial films.<sup>40</sup> For (111)-LaAlO<sub>3</sub>, our results suggest that none of the three polymorphs can be easily grown epitaxially due to relatively large values of MICA as well as strain energy. Experimentally<sup>40</sup>, the R/M phase was observed which could either be a result of a small interfacial buffer phase, or an indication of limiting factors (surface defects, interfacial chemistry) in the current model. Lastly, our model predicts that a (0001)-Al<sub>2</sub>O<sub>3</sub> (sapphire) substrate should favor epitaxial growth of a VO<sub>2</sub> A phase film, however R/M is frequently<sup>41</sup> found. Interestingly, it is worth noticing that Zhou et al.<sup>41</sup> did observe a transition or buffer layer at the VO<sub>2</sub>/(0001)-Al<sub>2</sub>O<sub>3</sub> interface, indicating that a direct epitaxial relationship may not exist between the substrate and the epitaxially grown film. A buffer layer is likely to favor the ground state, in this case the R/M phase, which explains the apparent mismatch between the theoretical prediction and experimental results. Overall, we find that the current model which incorporates a geometric unit cell area matching between the substrate and the target film as well as the resulting strain energy density of the film provide qualitative agreement with experimental observations, though a detailed nature of the lattice-substrate interface, e.g. the atomic orientation, termination preference and chemical character etc., require further research efforts.

Finally, with the ultimate goal of finding new polymorphs through targeted synthesis conditions and techniques, the aforementioned approach can also act as a preliminary sub-

Table 2: List of all heteroepitaxy substrates considered and analyzed for the growth of  $\text{VO}_2$  polymorphs

$\text{La}_2\text{Be}_2\text{O}_5$	$\text{BaAl}_2\text{O}_4$	$\text{ZnO}$	$\text{KTiAsO}_5$	$\text{Y}_3\text{Al}_5\text{O}_{12}$
$\text{Fe}_2\text{O}_3$	$\text{CdTe}$	$\text{SrTiO}_3$	$\text{LaAlO}_3$	$\text{TiO}_2$
$\text{YVO}_4$	$\text{Li}_2\text{B}_4\text{O}_7$	$\text{Ba}(\text{NO}_3)_2$	$\text{Au}$	$\text{AlN}$
$\text{Bi}_2\text{Te}_3$	$\text{CaF}_2$	$\text{CdS}$	$\text{BaTiO}_3$	$\text{Ge}(\text{Bi}_3\text{O}_5)_4$
$\text{MoSe}_2$	$\text{MgF}_2$	$\text{KTaO}_3$	$\text{GaN}$	$\text{Ge}_3(\text{BiO}_3)_4$
$\text{LiNbO}_3$	$\text{PbS}$	$\text{Gd}_3\text{Ga}_5\text{O}_{12}$	$\text{Ge}$	$\text{MgAl}_2\text{O}_4$
$\text{PbWO}_4$	$\text{CaAs}$	$\text{YAlO}_3$	$\text{LiTaO}_3$	$\text{Fe}_3\text{O}_4$
$\text{GaSb}$	$\text{GaP}$	$\text{ZnTe}$	$\text{KI}$	$\text{LiAlO}_2$
$\text{Mg}_2\text{SiO}_4$	$\text{CaTiO}_3$	$\text{Ba}_2\text{YCu}_3\text{O}_7$	$\text{GdScO}_3$	$\text{KBr}$
$\text{AlNi}$	$\text{TbScO}_3$	$\text{DyScO}_3$	$\text{LiF}$	$\text{LaF}_3$
$\text{BaF}_2$	$\text{KCl}$	$\text{ZnGeP}_2$	$\text{InP}$	$\text{Cu}$
$\text{NaCl}$	$\text{ZnSe}$	$\text{Ni}$	$\text{CdWO}_4$	$\text{LiGaO}_2$
$\text{Bi}_2\text{Se}_3$	$\text{Ag}$	$\text{MoS}_2$	$\text{Al}_2\text{O}_3$	$\text{InSb}$

strate selector for any target phase and any given pool of substrate materials. In the case of  $\text{VO}_2$ , we are interested in finding appropriate substrates for growing the hitherto hypothetical anatase, brookite and columbite polymorphs. Hence, we collected and screened 66 commonly used single-crystalline substrates (as listed in Table 2), where the lattice information is taken from the calculated compounds in the Materials Project. Figure 4 maps the MCIA and the corresponding elastic strain energy, for all possible orientation relationships between the A-Phase  $\text{VO}_2$  and the 66 considered substrates. First of all, we note that the MCIA and elastic energy are highly uncorrelated indicating that a geometric approach based on matching lattice vectors alone is unlikely to find a minimum energy relationship. For example, in Fig. 4 (see highlighted dashed red box) super-lattices present as vertically aligned points where the differences in elastic energies are due to the slightly different shear and normal deformations needed for the  $\text{VO}_2$  A-Phase to conform to the substrates. Secondly, we observe that - even compared to a larger substrate set - the homostructural growth relation ( $\text{VO}_2$  growth on  $\text{TiO}_2$ ) is well optimized in terms of the topological and strain matching metrics. Thirdly, Fig. 4 shows that while substrates such as  $\text{Al}_2\text{O}_3$  would be a conventional choice for heteroepitaxy, this approach can identify superior and unconventional substrates such as  $\text{Ba}_2\text{YCu}_3\text{O}_7$  that would be neglected by a conventional search. To stabilize the

anatase, brookite and columbite polymorphs, we select the substrate surface orientations that yield the smallest values for both MCIA and  $\Delta E_s$  for a particular  $\text{VO}_2$  polymorph. Our lattice match results suggest that (101)- $\text{CdWO}_4$  and 110- $\text{AlN}$  would be suitable for growing  $\text{VO}_2$  columbite and (100)- $\text{Ba}_2\text{YCu}_3\text{O}_7$ , (101)- $\text{LaAlO}_3$ , (111)- $\text{SrTiO}_3$ , (001)- $\text{BaTiO}_3$  and (001)- $\text{GaN}$  for growing anatase. For  $\text{VO}_2$  brookite, the following substrates are recommended: (001)- $\text{Fe}_3\text{O}_4$ , (111)- $\text{La}_2\text{Be}_2\text{O}_5$ , (101)- $\text{LiAlO}_2$ , (100)- $\text{LiTaO}_3$ , (011)- $\text{YAlO}_3$  and (001)- $\text{BaAl}_2\text{O}_4$ . In general, we emphasize that care should be taken to evaluate factors not considered here such as substrate stability, availability and epitaxial interface chemistry. A good example of this decision making process would be the epitaxial growth of A-phase, where (0001)- $\text{Al}_2\text{O}_3$  could serve as a conventional substrate, but closer examination of the MCIA/ $\Delta E_s$  space suggests that either (010)- $\text{Ba}_2\text{YCu}_3\text{O}_7$  or (001)- $\text{TiO}_2$  would be more appropriate. We note that a limiting case of heterostructural growth is the homostructural condition, which is found in this search methodology as the growth of A-phase  $\text{VO}_2$  on  $\text{TiO}_2$  and suggests that these two criteria nicely encompasses the homostructural growth case in the substrate selection process. As previously mentioned, we can also consider the total energy change under epitaxial strain. As an example, we consider the problem of stabilizing the  $\text{VO}_2$  columbite phase. An initial search would identify the substrate, and ideally the plane, that induces the largest strain energy difference between the desired phase and ground state. Considering the 66 substrates in Table 2, the most suitable substrate can be narrowed down to (011)-  $\text{YAlO}_3$ . Figure 5 shows the total energy as a function of the epitaxial strain for the six polymorphs of  $\text{VO}_2$  considered in this study on (011)-  $\text{YAlO}_3$ . The rutile phase is the lowest energy phase up to 3.6% strain, above which columbite exhibits the lowest energy. Hence, we predict that the (011)-  $\text{YAlO}_3$  substrate enables a phase-stability cross over at a modest strain of 3.6%, where columbite is promoted over the rutile  $\text{VO}_2$  ground state. While the epitaxial constrain preferentially stabilizes the columbite phase among the considered phases, we also note that the energy difference between columbite and brookite is very small even up to 9% total strain, which may limit the phase selectivity.

## 4 Conclusion

In summary, driven by the need for rational polymorph selection during synthesis, we present a computational framework involving a combination of first-principles calculations of formation energy, elastic strain energy and topological lattice matching. Using the outlined framework, we prescreen a set of optimal substrates for epitaxial growth, given a target material and/or polymorph. In a simple scenario we examine using homostructural growth selecting a chemically similar system based on common polymorph statistics, lattice matching and energy above hull. Specifically, for VO<sub>2</sub> polymorphs, we find - not surprisingly - that TiO<sub>2</sub> substrates, where the VO<sub>2</sub> brookite phase would be preferentially grown on the *a* - *c* plane while the columbite and anatase structures favor growth on the *a* - *b* plane. To support a more general selection scenario, we consider heterostructural growth, where the pool of candidate substrates can generally comprise any chemical system and the orientation relationship between the film and the substrate is obtained through a set of criteria based on the minimal interfacial geometry matching and estimated strain energy as a function of the substrate-film pair. Specifically, for the test case of VO<sub>2</sub> polymorphs we find that (101)-CdWO<sub>4</sub> and 110-AlN are recommended for growing VO<sub>2</sub> columbite and (100)-Ba<sub>2</sub>YCu<sub>3</sub>O<sub>7</sub>, (101)-LaAlO<sub>3</sub>, (111)-SrTiO<sub>3</sub>, (001)-BaTiO<sub>3</sub> and (001)-GaN for growing anatase. For VO<sub>2</sub> brookite, the following substrates are selected by the model: (001)-Fe<sub>3</sub>O<sub>4</sub>, (111)-La<sub>2</sub>Be<sub>2</sub>O<sub>5</sub>, (101)-LiAlO<sub>2</sub>, (100)-LiTaO<sub>3</sub>, (011)-YAlO<sub>3</sub> and (001)-BaAl<sub>2</sub>O<sub>4</sub>. In this work, while the energy contributions are presented and analyzed separately, it is straightforward to utilize a total energy vs strain criterion. This selection scheme is exemplified for the case of VO<sub>2</sub> columbite, which shows (011)- YAlO<sub>3</sub> to be a suitable substrate. In general, we recommend that the evaluation scheme is flexible and can change depending on the system, such that the total energy as well as its separate components be considered valid screening parameters. These methodologies will be implemented within the Materials Project. We found that the outlined framework and chosen criteria can be used as a preliminary guide for substrate selection and aid experimental efforts in stabilizing new materials and/or polymorphs as



well as to inspire further investigations into the governing principles of polymorph selection through epitaxy.

## 5 Acknowledgement

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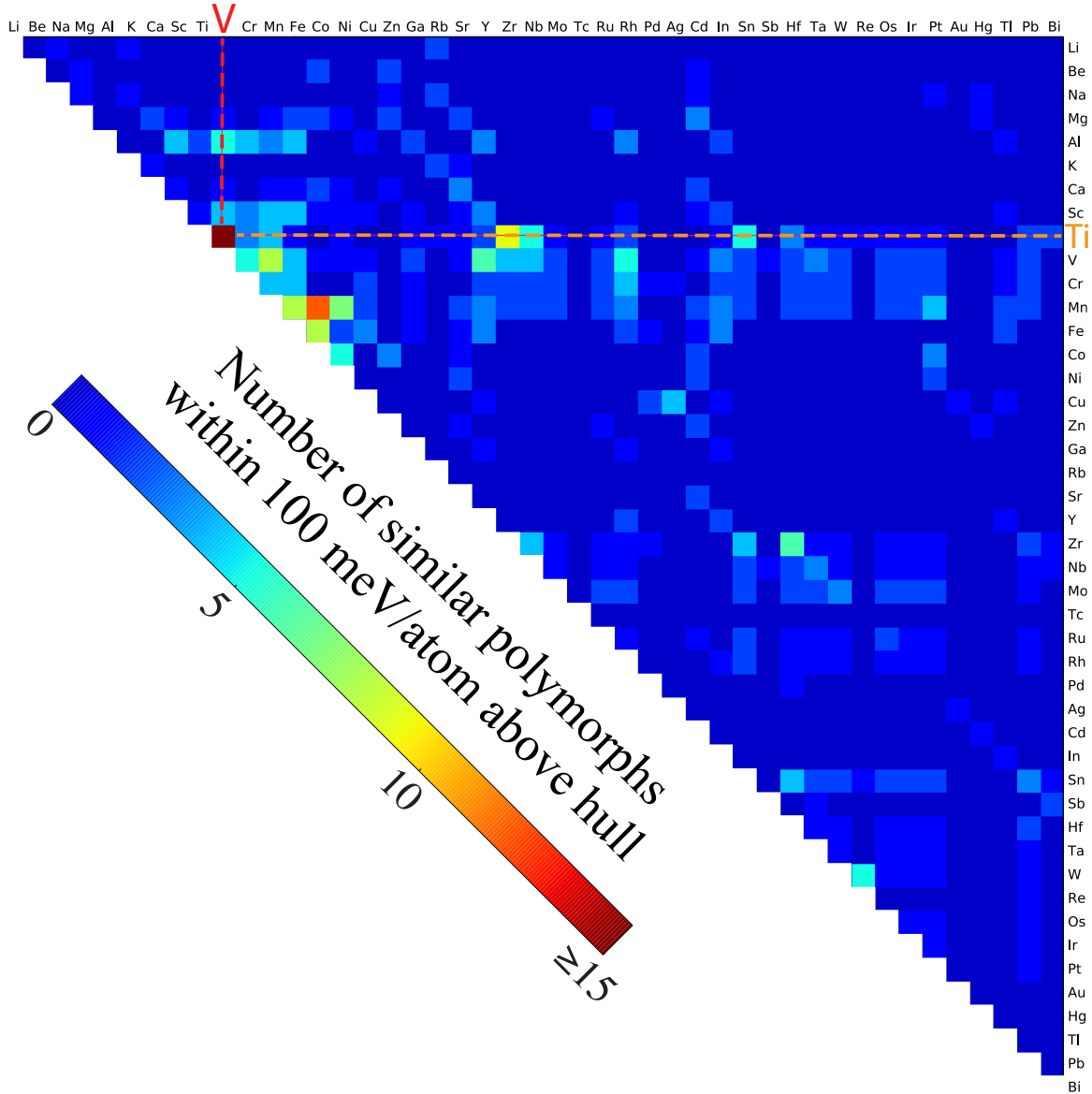


Figure 1: Illustration of the number of conformal oxide polymorphs within 100 meV/atom of the hull between two elements. Reddish color indicates a high number of shared polymorphs, indicating that the two elements would be ideal for oxide homoepitaxy. The data is taken from the Materials Project Database, which contains mainly experimentally verified compounds from the ICSD<sup>33</sup> but also an increasing number of 'hypothetical' structures created by ionic substitution, removal of ions, structure prediction methods etc. To obtain a measure of chemical similarity, the structures considered here were filtered on the "energy above Hull" less than 100 meV/atom, which provides a reasonable upper bound of accessible metastability.<sup>34</sup>

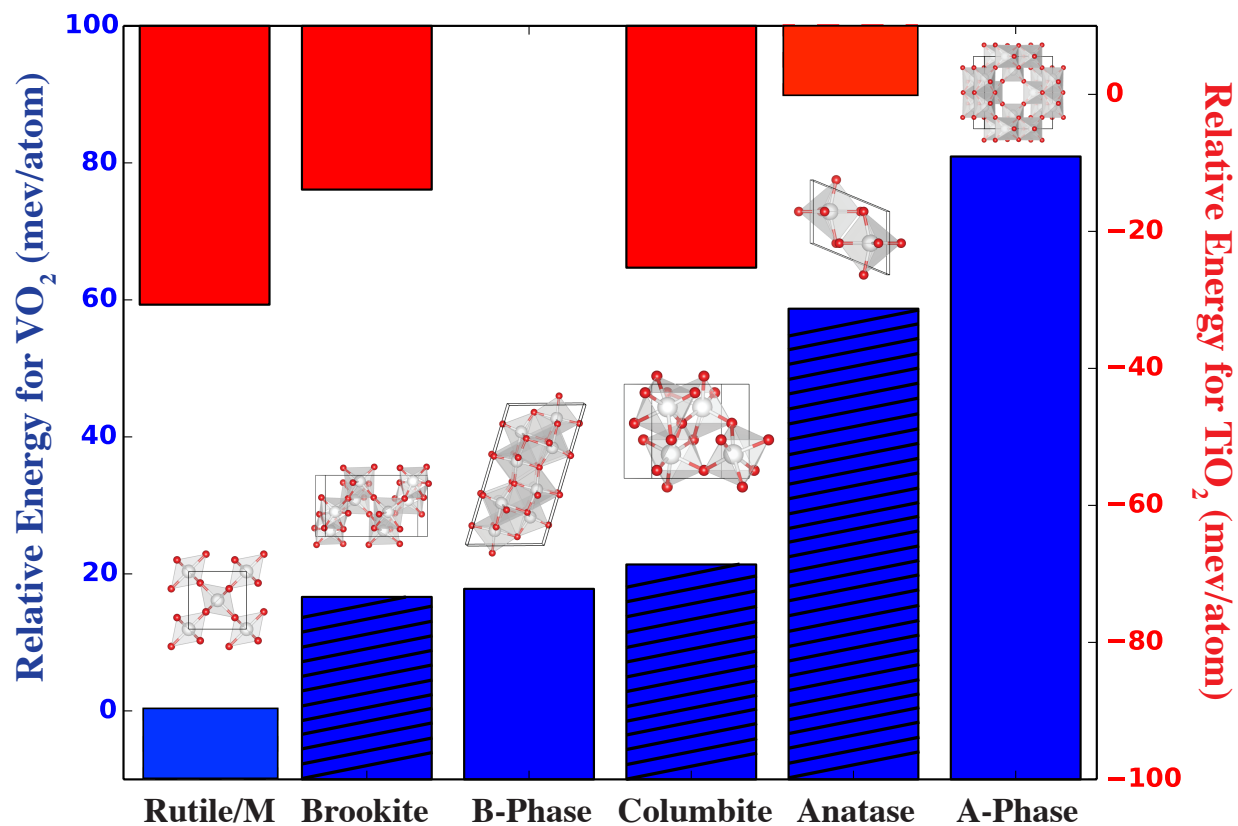


Figure 2: To estimate the accessible window of metastability we compare the calculated relative formation energies of various polymorphs in  $\text{TiO}_2$  (red) and  $\text{VO}_2$  (blue). The lowest-energy structure (anatase for  $\text{TiO}_2$  and rutile for  $\text{VO}_2$ ) is used as the reference state. Dashed bars indicate the polymorphs that have not been synthesized.

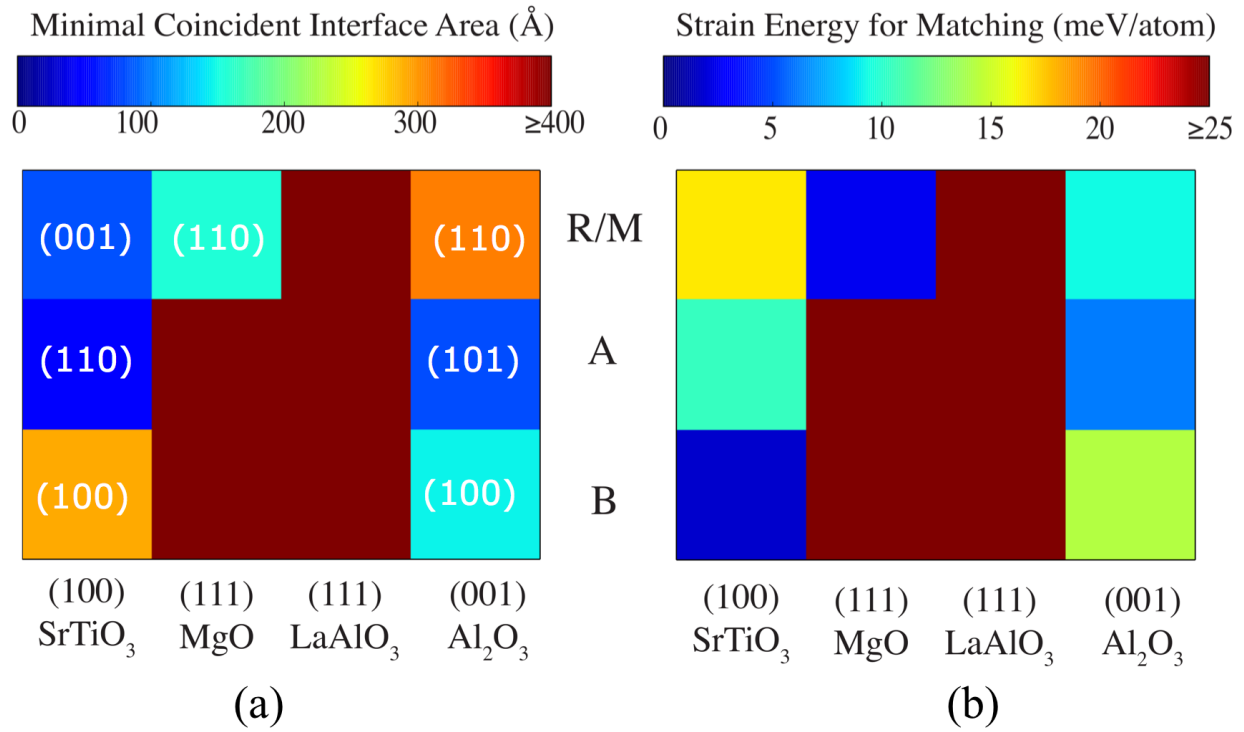


Figure 3: (a) The calculated minimal coincident interface area for substrate and VO<sub>2</sub> polymorph pairs and (b) the corresponding film strain energy. The orientation of the target film is labeled with the corresponding Miller index in (a)



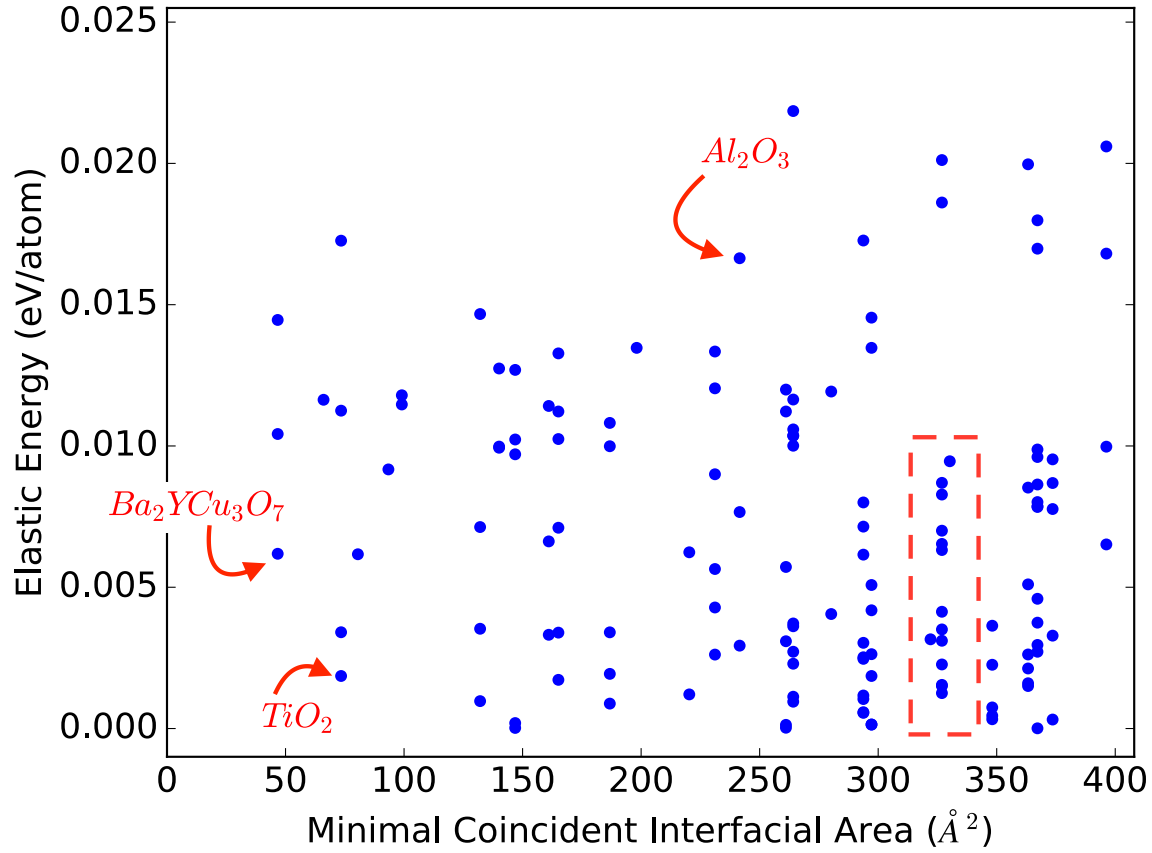


Figure 4: The minimal coincident interface area (MCIAs) and the corresponding strain energy density ( $\Delta E_s$  between A-Phase  $\text{VO}_2$  and 66 selected substrates). Red arrows highlight three different substrates for A-phase growth:  $\text{Al}_2\text{O}_3$  (MCIAs:  $73 \text{ \AA}^2$ :  $3 \text{ meV/atom}$ ),  $\text{Ba}_2\text{YCu}_3\text{O}_7$  (MCIAs:  $46 \text{ \AA}^2$ :  $6 \text{ meV/atom}$ ) and  $\text{TiO}_2$  (MCIAs:  $73 \text{ \AA}^2$ :  $1 \text{ meV/atom}$ ). One example of superlattice grouping is highlighted with a dashed red box.

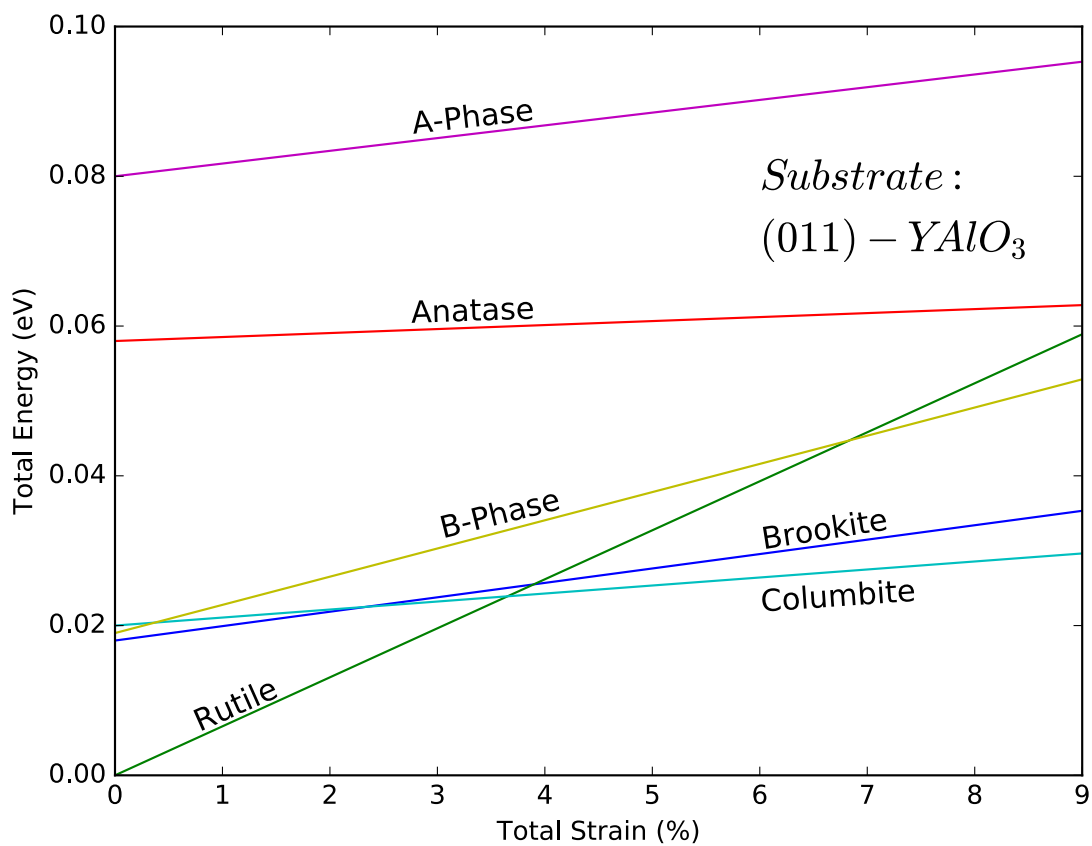


Figure 5: The total energy of  $VO_2$  polymorphs as strained on (110)-  $YAlO_3$  referenced to the unstrained rutile formation energy. The total energy is the sum of the formation energy and the elastic strain energy. Dashed red lines highlight one example of super-lattice grouping

**Substrate  
Database**



**Epitaxial  
Matching  
Database**



**Topology  
Filter**



**Energy  
Filter**



**Ideal  
Substrate**

**Structure  
Database**

