Competing strain effects in reactivity of LaCoO$_3$ with oxygen
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Planar strain effects on oxygen-vacancy formation and oxygen adsorption on LaCoO$_3$ are shown to manifest through competing mechanisms. Through first-principles calculations, we demonstrate that these unit processes are facilitated by elastic stretching. On the other hand, spin-state transitions and Co-O bond exchange hinder these processes by trapping the lattice oxygen with increasing tensile strain. A transition from chemisorption to physisorption of the oxygen molecule is identified at high strains. Insights on charge-density profiles, density of electronic states, and stress thresholds suggest the possibility of tuning strain-mediated reactivity in LaCoO$_3$ and related perovskite oxides.

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I. INTRODUCTION

External electromagnetic fields or mechanical strains give rise to unusual electronic and magnetic state transitions in a number of 3$d$ transition-metal (TM) oxides, such as the La$_{1-x}$Sr$_x$MnO$_3$ (LSM) (Ref. 1) and La$_{1-x}$Sr$_x$CoO$_3$ (LSC) (Ref. 2) families of perovskite compounds. In particular, LSC exhibits notable strain effects on its electrical transport and magnetic state.3–5 LSM and LSC also have been treated as model catalysts and mixed ionic and electronic conductors for high-temperature applications that involve oxygen reactions.5 In enabling fast oxygen reduction and transport through these materials, their surface and bulk reactivities play important roles. First-principles and atomistic calculations7–9 have shown the unit processes governing oxygen reduction to consist of oxygen molecule adsorption followed by dissociation into a neighboring oxygen vacancy and transport into the bulk through a vacancy-mediated mechanism. Thus, both the adsorption process and the equilibrium vacancy concentrations contribute to the TM oxide reactivity. While the underlying strain effects were shown to alter the stable oxygen-vacancy configurations in some oxide systems,10–12 systematic studies to clarify the competing microscopic mechanisms and the magnitude of these effects have not been carried out.

In this study, we determine the dominant strain-driven mechanisms governing oxygen-vacancy formation in the bulk, and oxygen molecular adsorption and vacancy formation on the surface of LaCoO$_3$ (LCO) by performing first-principles calculations. LaCoO$_3$ was chosen as a model system with no ionic or electronic defects. We treat these unit processes separately from each other, solely to probe the mechanistic effects of strain on them. Mavrikakis et al.13 showed that the surface reactivity of the metal increases with biaxial lattice expansion, following a concurrent upshift of the metal d state.13 For the TM perovskite, we find the picture is more complex. We identify the primary competing processes to be elastic stretching of the Co-O bonds which reduces the overlap of the Co $d$ and O $p$ bands, anisotropic local relaxations which break and reform the Co-O bonds, and phase transitions in spin state. The first two mechanisms are elastoplastic in nature while the third is magnetoelastic. We show that the elastoplastic effects cause a transition in the adsorption mechanism from chemisorption to physisorption. The magnetoelastic coupling introduces an additional degree of freedom, with the Co$^{3+}$ $d^6$ ion displaying various spin states due to a delicate balance between the crystal-field splitting and the intra-atomic Hund’s exchange.14 Variations in the Co-O bond length, the Co-O-Co angle, and the tilt pattern of the CoO$_6$ octahedra are known to be important in the magnetic and electronic-structure transitions in the strain-induced pseudotetragonal LCO.3,4 These in turn give rise to electron localization and Co-O bond strength alterations which are also important in the LCO reactivity.

An implication of this work is the prospect of controlling the TM oxide reactivity through strain to develop highly active ionic nanostructures in, for example, solid oxide fuel cells, sensors, and batteries. Nanoscale heterointerfaces which can introduce large coherent strains are a promising direction for this purpose.15,16 The examples to date include strained yttria stabilized zirconia (YSZ) (Refs. 17–19) and heterointerface of (La,Sr)$_2$CoO$_4$/La,Sr)CoO$_3$ (Ref. 20) thin films. These structures have been shown to exhibit several orders of magnitude higher ionic conductivity and oxygen exchange rate compared to their unstrained single-phase states. The mechanistic insights discussed here concerning strain-induced bulk and surface reactivities are not limited only to oxygen in LCO, they can be extended to other ionic TM oxides. Additionally, probing the strain response of the oxygen defects in the LSC family can give insights to the indirect chemical effects of strain on magnetic state transition mechanisms.21

II. SIMULATION APPROACH

We applied density-functional theory (DFT) formalism in the generalized gradient approximation parameterized by Perdew and Wang22 using plane-wave basis set to calculate the energetics described in this paper. To avoid the self-interaction errors that occur in the traditional DFT for
strongly correlated electronic systems, we employed the DFT+$U$ method accounting for the on-site Coulomb interaction in the localized $d$ or $f$ orbitals.\textsuperscript{23} The correction parameter of effective $U-J=3.3$ eV was chosen, as determined in Ref. 24 by fitting the enthalpies of oxidation reactions. The ionic cores were represented with projector-augmented wave\textsuperscript{8} was considered here as the most stable

KUSHIMA, YIP, AND YILDIZ PHYSICAL REVIEW B 82

\[ E_{\text{ad}} = E' - E_0 - E_{O_2}, \]

where $E_v$, $E'$, $E_0$, and $E_{O_2}$ are the system energies with one vacancy, adsorbed $O_2$, no vacancy or $O_2$, and an isolated $O_2$ molecule, respectively.

The maximum strain considered here was 15%. When a vacancy was introduced beyond 11% strain, the bulk cations were restrained to their perovskite positions. These very large strains cannot be supported by LCO films of tens or hundreds of nanometer thickness grown on a substrate.\textsuperscript{26} We treat the structure and strain conditions here as an ideal defect-free system in probing the dominant mechanisms operating on the oxygen sublattice under strain. Real defected LCO structures may exhibit similar phenomenon as identified here, at smaller global strain states. Such large strain states could be achieved only locally, for example, in the vicinity of dopants of different radii\textsuperscript{29} and extended defects.

III. RESULTS AND DISCUSSION

A. Bulk reactivity vs strain

We present first our results on bulk reactivity, namely, the vacancy formation energy, $E_{\text{vac}}^B$, which determines the equilibrium anion vacancy concentration. Lower value of $E_{\text{vac}}^B$ means vacancy formation is favored, which also enables more facile kinetics of incorporation of the adsorbed oxygen into the bulk and its ionic transport therein. Figure 2 shows the variations in $E_{\text{vac}}^B$ and the magnetic moment, $\mu_B$/Co, with tensile lattice strain in LCO. In the unstrained state, the LCO bulk is at the low-spin (LS) state. It is reasonable to expect that in general tensile strain, in the form of elastic stretching, will act to lower $E_{\text{vac}}^B$ by weakening the Co-O bond, as is the case here up to $\varepsilon = 0.02$ shown in Fig. 3. However, two significant reversals of this trend are seen, at $\varepsilon = 0.03$ and again at $\varepsilon = 0.11$. The first increase in $E_{\text{vac}}^B$ is very well correlated with the jump in magnetic moment at $\varepsilon = 0.03$. Thus, this reversal is attributed to a spin transition from the state LS, characterized by a cubiliclike charge-density distribution around the Co ion,\textsuperscript{30} to the intermediate-spin (IS) state with a spherical distribution and stronger Co-O overlap, as can be seen in Fig. 3. At the strain $\varepsilon = 0.11$, where the second reversal occurs, we find the atomic configuration undergoes a lo-
Cal rebonding with rupture of two nearest-neighbor Co–O bonds in the xy plane and strengthening of the other two, again seen in Fig. 3. This configurational change results in the trapping of two oxygen ions for each Co and increase in $E_{\text{vac}}^0$. Our claims of bond strengthening and weakening induced by the magnetoelastic and elastoplastic transitions here are supported by our density of states (DOS) calculations showing the extent of the hybridization between the Co $d$ bands and O $p$ bands. Orbital projected DOS for Co $d$ orbital and O $p$ orbital at various strains are shown in Fig. 4. Overlapping of Co $d$ orbital and O $p$ orbital depicts the orbital hybridization and Co–O binding in the bulk of LaCoO$_3$. At $\varepsilon = 0.00$, strong hybridization of the DOS peaks at $-4$ eV and $-4.7$ eV is evident. As lattice strain increases up to $\varepsilon = 0.02$, the overlap of the peaks decreases, indicating the weakening of the Co–O bond during elastic stretching. This decrease in the hybridization driven by elastic stretching was reversed twice at larger strains. First at $\varepsilon = 0.03$ where the spin state changes from LS to IS, the hybridization of the Co $d$ orbital and O $p$ orbital in DOS reemerges near $-6$ eV. At $0.03 < \varepsilon < 0.10$, the overlap in the DOS peaks decreases again due to the elastic stretching of the Co–O bonds in the IS state, corresponding to the second decrease in $E_{\text{vac}}^0$. Second, beyond $\varepsilon = 0.10$, hybridization of the Co $d$ orbital and O $p$ orbital strengthens near $-5$ eV because of the strengthening of the Co–O bond, and increases the $E_{\text{vac}}^0$. O–cation bond strengthening and the trapping of oxygen due to local relaxations at high strain states has been demonstrated in YSZ under tensile planar strain, consistent with our observations here for LCO, although in the present case the magnetoelastic coupling in the LCO bulk added an extra degree of complexity to the relationship between strain and vacancy formation energy.

**B. Surface reactivity vs strain**

Next, we probe surface reactivities through oxygen adsorption and vacancy formation energies, $E_{\text{ad}}$ and $E_{\text{vac}}^S$. Their variations with lattice strain are shown in Fig. 5. Unlike the LS state in the bulk, the LCO surface was in state IS at $\varepsilon = 0.00$. We can again interpret the strain responses in terms of the charge-density distributions and local density of states both explicitly reported here. Compared to Fig. 2, Fig. 5 indicates only a single reversal of the tensile strain effect, at $\varepsilon = 0.04$. Given the foregoing discussion on bulk reactivity, this is to be expected in the absence of a spin-state transition. For $\varepsilon > 0.03$, we find significant strengthening of the Co–O bond due to local relaxations that trap oxygen, similar to that discussed above for bulk LCO at high strain.

The strain response of $E_{\text{ad}}$ exhibits a similar trend as that of $E_{\text{vac}}^S$. At low strains, $\varepsilon \leq 0.04$, the O$_2$ molecule chemisorbs on a Co ion, with its $p$ orbital hybridizing with the Co $d$ orbital and O $p$ orbital at various strains are shown in Fig. 4. Overlapping of Co $d$ orbital and O $p$ orbital depicts the orbital hybridization and Co–O binding in the bulk of LaCoO$_3$. At $\varepsilon = 0.00$, strong hybridization of the DOS peaks at $-4$ eV and $-4.7$ eV is evident. As lattice strain increases up to $\varepsilon = 0.02$, the overlap of the peaks decreases, indicating the weakening of the Co–O bond during elastic stretching. This decrease in the hybridization driven by elastic stretching was reversed twice at larger strains. First at $\varepsilon = 0.03$ where the spin state changes from LS to IS, the hybridization of the Co $d$ orbital and O $p$ orbital in DOS reemerges near $-6$ eV. At $0.03 < \varepsilon < 0.10$, the overlap in the DOS peaks decreases again due to the elastic stretching of the Co–O bonds in the IS state, corresponding to the second decrease in $E_{\text{vac}}^0$. Second, beyond $\varepsilon = 0.10$, hybridization of the Co $d$ orbital and O $p$ orbital strengthens near $-5$ eV because of the strengthening of the Co–O bond, and increases the $E_{\text{vac}}^0$. O–cation bond strengthening and the trapping of oxygen due to local relaxations at high strain states has been demonstrated in YSZ under tensile planar strain, consistent with our observations here for LCO, although in the present case the magnetoelastic coupling in the LCO bulk added an extra degree of complexity to the relationship between strain and vacancy formation energy.

**FIG. 3.** (Color online) Electronic charge-density distribution of the valence electrons on the CoO$_2$ xy plane as a function of strain, $\varepsilon$, before the introduction of oxygen vacancy to the model. Large spheres are Co and small spheres are O atoms.

**FIG. 4.** (Color online) Orbital projected electronic density of states (DOS) for the Co $d$ orbital and O $p$ orbital with varying extent of hybridization at different strains in the bulk LaCoO$_3$ model. Arrows show the O $p$ and Co $d$ orbitals' hybridization.

**FIG. 5.** (Color online) Vacancy formation energy $E_{\text{vac}}^S$ (circles), oxygen adsorption energy $E_{\text{ad}}$ (squares), and magnetization (triangles) on the LaCoO$_3$ surface as a function of lattice strain.
orbital. This hybridization forms three prominently overlapped peaks, indicated by the arrows in Fig. 6(a)—upper panel. Furthermore, oxygen adsorption spreads and downshifts the Co d band. Here, the large change in Co d-band DOS after the adsorption implies the O$_2$ was chemisorbed to the surface Co.

Figure 7(a) shows that the Co d-band center on the LaCoO$_3$ surface without an adsorbed O$_2$ molecule increases monotonically with tensile strain. Reduction in $E_{ad}$ with tensile strain due to the upshift of the d-orbital energy and the reduction in coordination was reported on transition-metal surfaces. This agrees with the decrease in $E_{ad}$ in our calculations for $\varepsilon \leq 0.03$, corresponding to the upshift of the Co d band. We also consider the Co d-band center on the LaCoO$_3$ surface “with” an adsorbed O$_2$ molecule, which downshifts with strain as shown in Fig. 7(b). The downshift of this d-band energy from the bare state to the oxygen adsorption state is a measure of the relative relaxation of the system energy upon oxygen adsorption. The shift becomes more negative for $\varepsilon \leq 0.03$. The relative increase in the magnitude of this downshift for $\varepsilon \leq 0.03$ means that the system energy reduces by a larger amount upon oxygen chemisorption when strained, and thus, favors “stronger” chemisorption with lower $E_{ad}$. From $\varepsilon = 0.03$ to $\varepsilon = 0.04$, the Co d-band center further increases on the LaCoO$_3$ surface without an adsorbed O$_2$ molecule. On the other hand, the shift of the Co d-band center on the LaCoO$_3$ surface with the adsorbed O$_2$ molecule becomes strongly positive at $\varepsilon = 0.04$. This suggests that the O$_2$ adsorbed state becomes relatively less stable, and thus the increase in $E_{ad}$ beyond $\varepsilon = 0.03$. Furthermore, at $\varepsilon \approx 0.04$, we observe stark differences in the local O d- and O p-orbital DOS. When $\varepsilon \approx 0.04$, two separate peaks of the O p orbital remains with only a small overlap with the Co d orbital [Fig. 6(b) for $\varepsilon = 0.04$] and does not modify the Co d-band DOS noticeably. This indicates that the oxygen adsorption mechanism changes from chemisorption to physisorption. As a result, the Co d-band shift becomes larger at higher strain, making O$_2$ adsorption less stable [Figs. 5 and 7(b)]. This transition coincides with the local relaxations beyond $\varepsilon = 0.03$. This elastoplastic configuration change is illustrated in Fig. 8. The surface has nonuniform bond lengths even at $\varepsilon = 0.0$. The longer bond $l_1$ increases while $l_2$ stays nearly constant up to $\varepsilon = 0.03$. Contracting of $l_2$ along with faster elongation of $l_1$ for $\varepsilon > 0.03$ signifies that the longer bond $l_1$ was broken. At this point, $l_1$ reaches the maximum bond length [dashed horizontal line in Fig. 8(b)].
of 2.16 Å. This bond length corresponds to the value incipient to the local relaxation in the bulk LCO model at $\varepsilon = 0.11$, and this criterion also supports the breaking of the Co-O $I_1$ bond on the surface. Consequently, the surface Co can bind more strongly to some of its neighboring O atoms, and therefore could not provide its electrons to hybridize appreciably with the adsorbing oxygen molecule. Once again, from $\varepsilon = 0.04$ to $\varepsilon = 0.05$ increasing the strain facilitates adsorption as reflected in the decrease in $E_{ad}$ but now in the physisorption mode.

IV. CONCLUSION

The capacity of the material to sustain the stress imposed by the strain state is the critical factor that influences the Co-O bonding to either favor or disfavor the energetics discussed in this work. Figure 9(a) shows the strain states at which the stress drops in the bulk and in the film, when a spin-state transition takes place or when there are local relaxations. The spin-state transitions are shown in Fig. 9(b); they coincide well with the stress relaxations from 0.62 to 0.32 GPa at $\varepsilon = 0.01$ for the film, and from 6.3 to 2.3 GPa at $\varepsilon = 0.03$ in the bulk LaCoO$_3$ models. There is no spin-state transition on the surface of the LaCoO$_3$ film model. The

The magnetoelastic transition in the bulk correlated well with the significant increase in $E_{ad}$ shown in Fig. 2. The decrease in the stress at higher strains, specifically around $\varepsilon = 0.13$ for the bulk model and $\varepsilon = 0.04$ for the film model corresponds to the Co-O bond breaking and reforming during local relaxations. This elastoplastic transition governed the increase in the $E_{ad}^{B,S,B}$ and $E_{ad}$. Local stress relaxations at high strain states create stronger Co-O bonds, trapping the lattice oxygen with higher $E_{ad}^{S,B}$ and disfavoring chemisorption with higher $E_{ad}$. Spin-state transition from LS to IS strengthens the Co-O bonds and increases $E_{ad}^B$. In particular, we discovered the competition of the magnetoelastic versus elastoplastic effects on oxygen-vacancy formation, and the change in the $O_2$ adsorption mechanism from chemisorption to physisorption at large strains. Our results illustrate the exciting potential of modulating the reactivity by controlling the strain state of LaCoO$_3$, related perovskite oxides and other ionic materials that exhibit strain-driven transitions in magnetic or electronic structure. Beyond uniform planar strain in thin films, the strain fields around the dislocations can also be considered for modulating the reactivity of such oxide systems. The insights obtained here are also important for motivating experimental and theoretical work to separate out the indirect chemical effects of strain from its direct effects on the magnetic state transitions.

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