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Resolving the adsorption of molecular O_2 on the rutile $TiO_2(110)$ surface by non-contact atomic force microscopy

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Interaction of molecular oxygen with semiconducting oxide surfaces plays a key role in many technologies. The topic is difficult to approach both by experiment and theory, mainly due to multiple stable charge states, adsorption configurations and reaction channels of adsorbed oxygen species. Here we use a combination of non-contact atomic force microscopy (AFM) and density functional theory (DFT) to resolve O_2 adsorption on the rutile $TiO_2(110)$ surface, which presents a long-standing challenge in the surface chemistry of metal oxides. We show that chemically inert AFM tips terminated by an oxygen adatom provide excellent resolution of both the adsorbed species and the oxygen sublattice of the substrate. Adsorbed O_2 molecules can accept either one or two electron polarons from the surface, forming superoxo or peroxo species. The peroxo state is energetically preferred under any conditions relevant for applications. The possibility of non-intrusive imaging allows us to explain behaviors related to electron/hole injection from the tip, interaction with UV light, and the effect of thermal annealing.

O_2 | Oxides | TiO_2 | nc-AFM | Tip functionalization | Photochemistry | Photocatalysis |

Interaction of O_2 with metal oxide surfaces plays a key role in many applications including gas sensing (1), heterogeneous catalysis (2), the oxygen evolution (3) and oxygen reduction reactions (4), or memristive switching (5). The rutile $TiO_2(110)$ is considered a prototypical metal oxide surface (6), and adsorption of molecular oxygen on this material has attracted a lot of attention over the past decades (7–14). Despite extensive work on this fundamental problem even basic O_2 adsorption configurations have remained unclear, which has lead to puzzling observations regarding the thermal and photochemistry of this important molecule. We demonstrate that the superior resolution and non-intrusive imaging possible with non-contact atomic force microscopy (nc-AFM) (15) allows resolving these open questions.

Within the last decade, nc-AFM has achieved tremendous success including sub-molecular imaging of organic molecules (16), chemical discrimination of surface atoms (17), or measuring and manipulating the charge state of single atoms and molecules (18). While nc-AFM is an ideal tool to for studying metal oxides, it is not yet as widely employed as one could expect. The main impediment is the strong tip-dependence of the AFM images; there is no well-established tip functionalization suitable for metal oxide surfaces, unlike, for example, the CO-terminated tips regularly used for imaging organic molecules (19, 20). Our work reveals a purposed tip functionalization by an O adatom as a very promising approach. Such tips allow imaging the surface oxygen sublattice in the repulsive regime without chemical interaction with neither the substrate nor the oxygen adsorbates, and provide excellent lateral resolution.

Oxygen molecules prefer dissociative adsorption when dosed on a $TiO_2(110)$ surface with oxygen vacancies (V_O) at room temperature (21–28). On the other hand, the results of low-temperature O_2 dosing (<150 K) are ambiguous: Scanning probe techniques mostly report dissociative adsorption (28–31), while area-averaging techniques show a strong preference for molecular adsorption (31–44). The adsorption of molecular O_2 inside a Vo was the first adsorption hypothesis confirmed experimentally (45–49) and calculated to be the preferred configuration (50–56). Later, it was deduced that O_2 molecules can also chemisorb to the rows of five-fold coordinated Ti atoms (Ti_{5c}) (47–49), while DFT calculations mostly predict these species as the second most favorable molecular adsorption configuration (50–59). The exact O_2 adsorption configurations however, and the temperature range in which they are present, still remain unclear. The standard analysis technique,

Significance Statement

The interaction of molecular O_2 with semiconducting metal oxides, the adsorption configurations, response to thermal treatment, UV irradiation, and electron/hole injection, is at the heart of a wide range of technologies. These processes were studied molecule-by-molecule on the prototypical model oxide $TiO_2(110)$ using non-contact AFM. We show that the non-intrusive nature of the nc-AFM, and its exceptional spatial resolution due to the functionalization of the tip with a terminal O atom , allow identifying the oxygen adsorption geometries which were not previously determined by other techniques. In combination with theoretical calculations, we explain the charge states of the various adsorbed oxygen species, their dynamics upon annealing and UV irradiation, and the role of electron exchange with the TiO_2 substrate.

Author contributions: I.S., M. Schmid, C.F., U.D., and M. Setvín designed research; I.S., M.Č., M.W., and M. Setvín conducted measurements; I.S., M.R., and C.F. performed calculations and simulations. All authors discussed and wrote the paper.

The authors declare no conflict of interest.

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scanning tunneling microscopy (STM), can easily dissociate the adsorbed molecules and requires very delicate conditions to avoid manipulation of the molecular O_2 (45–49). Using a non-intrusive local nc-AFM technique has already proven promising by observing one O_2 molecular species on the Ti_{5c} rows (26, 27). The functionalization of the nc-AFM tip by an O atom provides sharper resolution. Our study reveals that there are, in fact, three distinct O_2 species on the surface, one in the vacancy and two at the Ti_{5c} rows, coordinated to either one or two Ti atoms. Each of these species shows a different behavior upon annealing or UV light irradiation.

On stoichiometric $TiO_2(110)$ surfaces, the molecular O_2 only physisorbs (60, 61). Electron donation from the surface, resulting in an O_2 anion, is required for the chemisorption (59). The surface excess electrons mostly originate from the intrinsic bridging oxygen vacancy defect (V_O), but can also be provided either by coadsorbates (for example OH) or titanium interstitials (Ti_{int}) (59). The charge state of the adsorbed O_2 molecules has been discussed for a long time with major disagreement between experiment and theory. While theory mostly assigns the adsorbed molecules to be doubly negative, *i.e.*, in the peroxo state (50–53, 57–59), experimental data were often interpreted as singly charged negative, *i.e.*, superoxo molecules (37–43, 48). The charge state of the adsorbed O_2 affects the adsorption geometry. Our highly-resolved data allow a direct comparison with calculation results, confirming the predicted peroxo state.

Chemisorbed molecular O_2 was observed to desorb from the surface at ≈400 K in temperature-programmed desorption (TPD) experiments (31–33, 37, 39), yet the origin of this peak remains clouded due to the diffusion of titanium interstitials from the bulk that is also activated close to this temperature (28, 33, 62). In annealing excursions, we follow the different O_2 species in, and identify their fate.

In contrast to the sharp peak in TPD, the desorption of molecular O_2 under UV light show fast initial O_2 desorption followed by a long tail of slowly desorbing O_2 molecules (37–43). Via direct observation of the photo-induced O_2 reaction products after short and long UV exposures, we determine which molecules contribute to the fast and slow desorption channels. In combination with tip-induced charge injection experiments, we also clarify the hole or electron-induced nature of the various processes, and whether a one or two-step process is at work.

The three coexisting molecular species, and their adsorption properties and dynamic behavior, explain the rich surface chemistry of O_2 on $TiO_2(110)$. Our tip functionalization, verified in quantitative force-distance curves above various adsorbates, should prove invaluable for future AFM investigations on oxide surfaces.

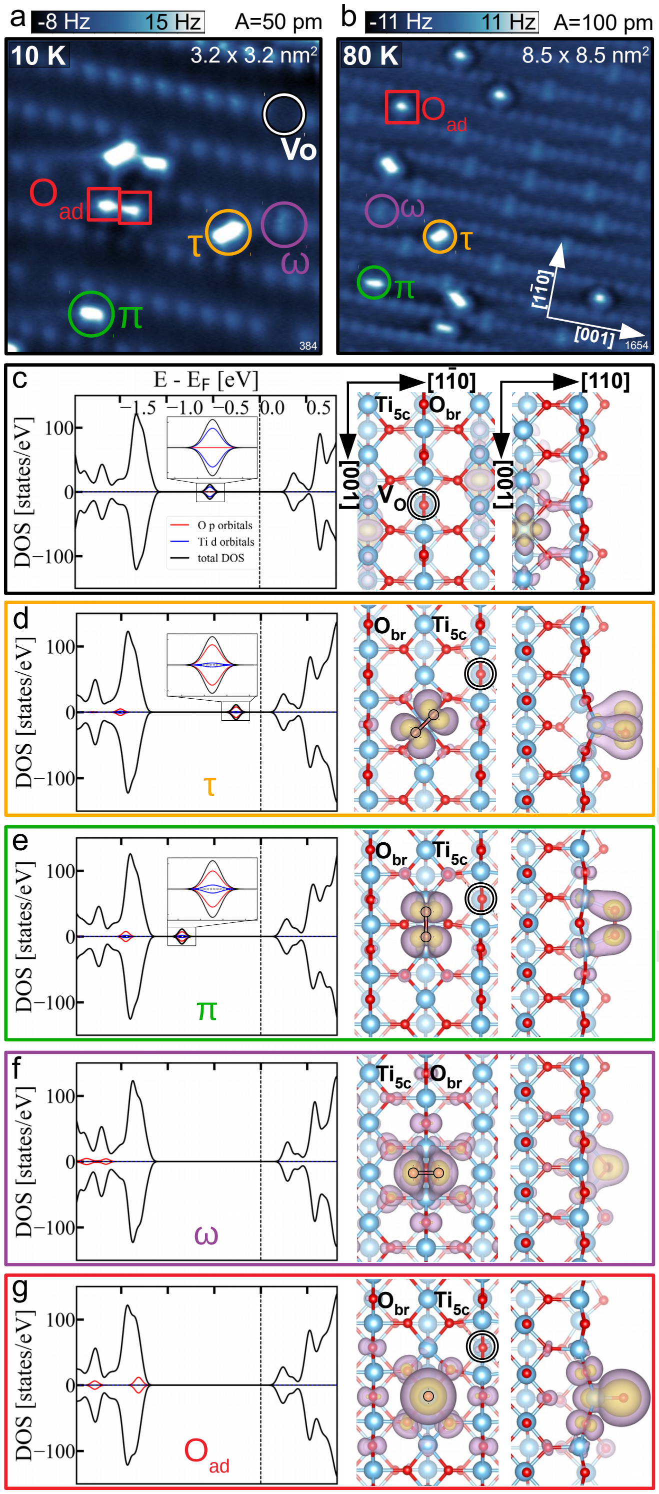
1. Results

A. O_2 adsorption configurations. The constant-height AFM images in Figures 1a and 1b show the rutile (110) surface with adsorbed oxygen. The image contrast is predominantly formed by repulsion between the O-functionalized tip apex and surface O atoms. The geometrically protruding rows of surface bridging oxygen (O_{br}) atoms are clearly resolved, occasionally interrupted by oxygen vacancies (Vo) (6). Such an image contrast provides direct access to the oxygen anion sublattice of the surface, and complements the cation sublattice contrast typically obtained in STM imaging (63).

Fig. 1a shows a surface with an initial concentration of oxygen vacancies of $c_{V_O} \approx 0.05$ ML, subsequently exposed to 0.1 Langmuir (L) of O_2 at a sample temperature of 10 K (measured at 4.8 K). Some oxygen vacancies remain unoccupied (marked with a white circle in Fig. 1a), while others are populated with an O_2 molecule (marked by a purple circle in the AFM images). These molecules are adsorbed with their bond axis in the [1-10] direction, perpendicular to the direction of the O_{br} rows. The appearance of these molecules in the AFM images indicates that they lie flat, incorporated in an O_{br} row. There are two molecularly bound O_2 species on the Ti_{5c} rows (O_2/Ti_{5c}), both flat according to the equal frequency shift over the constituent atoms inside each molecule. The molecule with its bond axis aligned parallel to the [001] direction of O_{br} rows (marked with a green circle in the AFM images) is bound to two underlying, neighboring, Ti_{5c} atoms. The molecule with the bond axis rotated by 45° towards the O_{br} rows (marked with an orange circle in the AFM images) is bound to only one Ti_{5c} atom directly underneath. We use the following nomenclature for the molecules: ω for the molecules inside the **o**xygen vacancy, π for the molecules **p**aralell to the O_{br} rows and τ for the molecules **t**urned towards the O_{br} rows. We note that τ and π molecules are not only differently rotated but also in different adsorption sites, shifted half a unit cell along [001].

The last species present in Fig. 1a are oxygen adatoms (marked with a red square in the AFM images), originating from dissociation of molecular oxygen. Oxygen does not spontaneously dissociate at this temperature. In Fig. 1a, oxygen adatoms were created by tip-induced dissociation in order to have all species present in a single image. Here, a voltage pulse of +1.3 V was applied to dissociate one π molecule. The adatoms commonly appear as isolated spheres located directly above one Ti_{5c} atom (red square in Fig. 1b). Their unusual, asymmetric contrast in Fig. 1a is a consequence of their mutual proximity and tip bending (64, 65).

Figures 1c–g show DFT+U results for the optimized geometries and corresponding density of states (DOS) of the various molecular configurations and the oxygen adatom present on the surface. Calculated adsorption energies E_{ads}, oxygen bond lengths $d(O_2)$, Bader charges Q_B, and spin states of the adsorbates are summarized in the table in Fig. 1h. The calculations were performed by adsorbing a single O_2 or O on a reduced 6×2 slab surface slab with one V_O. This corresponds to a V_O concentration of 1/12 ML (=8.3 %), similar to the experimental conditions. Fig. 1c shows the ground state of the reduced slab as a starting point of each adsorption scenario. The oxygen vacancy is a donor, which provides two excess electrons to the slab. These electrons form small polarons due to their coupling with lattice distortions, and they preferentially localize on the next-nearest subsurface Ti_{6c} atoms (66–69). They form the characteristic Ti^{3+} in-gap states in the calculated DOS shown in the left panel of Fig. 1c, and enlarged in the inset, while their spatial distribution (right panel of Fig. 1c) confirms their localization on polaron-hosting subsurface six-fold coordinated titanium atoms (Ti_{6c}). The presence of adsorbates can significantly affect the polaronic ground state of this surface (70). Figures 1d–g show the slab after adsorbing the oxygen species in geometries corresponding to the AFM measurements (τ, π, ω, and O_{ad}, respectively), with the DOS



h

	E_{ads} [eV]	d(O_2) [Å]	Q_B [e$^-$]	spin state
τ	-1.17	1.48	0.92	↑↓
π	-1.53	1.46	0.95	↑↓
ω	-2.03	1.49	1.12	↑↓
O_{ad}	-1.57	—	0.83	↑↓

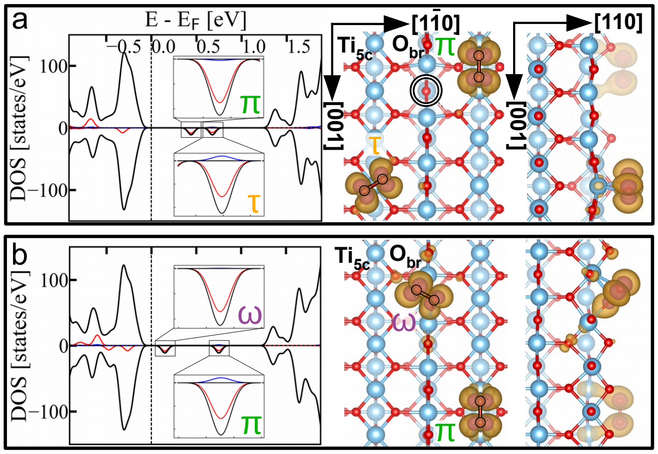
Fig. 1. Adsorbed molecular O_2 and atomic O. a, b) Constant-height AFM images obtained after O_2 dosing at 10 K and 80 K respectively, showing adsorbed molecular O_2 (circles) and atomic O species (squares). c) DFT calculation of the polaronic ground state of the clean, reduced surface with one bridging-oxygen vacancy. Left: The total DOS (black) and the partial contributions of the adsorbed O atoms (red) and their nearest Ti atoms (blue). The in-gap state is magnified in the inset. Right: Partial charge-density plots showing the top and the side view of the charge distribution of the two excess electrons originating from the V_O. d–f) DFT calculations of the molecular O_2 and g) atomic O adsorption configurations marked in constant-height AFM images, together with their respective names in the nomenclature adopted throughout the paper. h) Table summarizing the adsorption energy E_{ads} and spin states of the adsorbates, O–O bond lengths d(O2) and Bader charges Q_B of the τ, π, and ω molecules, and the Bader charge Q_B of the oxygen adatom O_{ad}.

plots and structure images organized as in Fig. 1c. Common to the presence of all adsorbed species is depletion of the polaron state. As a consequence, there is a dramatic change of the in-gap state of the clean, reduced slab; the in-gap state even shifts into the valence band in Figures 1f–g.

The τ molecule (Fig. 1d) is calculated to have the weakest adsorption energy, followed by the π molecule (Fig. 1e). Both molecules preserve an in-gap state in the total DOS. The origin of the in-gap state, enlarged in the insets, clearly illustrates a charge transfer from the polaron-hosting Ti_{6c} sites to the $2\pi^*$ orbitals of the adsorbed molecules. The spatial distribution of these two in-gap electrons is illustrated in the right side of the panels. They are shared between the constituent atoms within an O_2 molecule and preserve their opposite spins, yielding a zero net magnetization on the molecule. Therefore, both π and τ molecules accept two available polaronic electrons from the slab, making them peroxo molecules O_2^{2-}. Bader charges of the covalently bound adsorbates are usually significantly lower than the formal charges (71–73), since they do not account for the electrons used in the covalent bond formation to the underlying Ti atom(s). Bader charge of the molecules (74) (sum of Bader charges of the constituent atoms) of $Q_B \approx 1$ implies that roughly one electronic charge is spent on creating two chemical bonds to the underlying Ti atom(s) to which these molecules are directly bound. The calculated bond lengths of 1.46 Å and 1.48 Å for the π and τ molecule, respectively, are larger than in an O_2 in the gas phase (DFT value 1.28 Å) and support their peroxo assignment (75).

The calculated molecular species with the highest adsorption energy is the ω molecule (Fig. 1f). This adsorption configuration is characterized by the disappearance of the in-gap state and the corresponding states are shifted deep into the valence band. The spatial charge distribution plot in Fig. 1f shows the sum of all p-type contributions from the molecular states of the ω molecule. Due to the complete disappearance of the in-gap state and the appearance of symmetric features in the projected DOS on this molecule, we conclude that two excess electrons of opposite spin, present in the reduced slab, have been transfered to the ω molecule, again making it a peroxo O_2^{2-} species. A calculated bond length of 1.48 Å, no net magnetization, and a Bader charge larger than 1 confirm the charge transfer and peroxo character.

Simulating adsorption of an isolated oxygen adatom on top of a Ti_{5c} atom (Fig. 1g) also shows the disappearance of the in-gap state. The p-type states associated with the adatom are shifted to the valence band and indicate the transfer of all the excess electrons to the adatom, making it a doubly negative ionosorbed O_{ad}^{2-} atom. All adsorbed species in Figures 1d–g



c

		E_{ads} [eV]	$d(O_2)$ [Å]	Q_B [e^-]	spin state
&	π	-0.69	1.38	0.58	↑
	τ	per O_2	1.39	0.48	↑
&	ω	-0.74	1.39	0.66	↑
	π	per O_2	1.38	0.57	↑

Fig. 2. Stable superoxo species. a) Calculations of the co-adsorption of π and τ molecules and b) ω and π molecules to the slab with one V_O. The inset in the calculated DOS magnifies the unoccupied in-gap states residing on the adsorbed molecules, and the partial-charge-density plots show the spatial distribution of these unoccupied in-gap states. c) Table summarizing the adsorption energy per molecule E_{ads}, O–O the bond length $d(O_2)$, Bader charge Q_B, and the spin state of each molecule in the co-adsorption calculations.

were placed in their minimum-energy positions with respect to the empty V_O, see Fig. SM1.

Fig. 1b show the surface after dosing 0.5 L of oxygen at $T = 80$ K. At these conditions, all oxygen vacancies are filled by ω molecules, and additional π and τ molecules adsorb on the Ti$_{5c}$ rows. The saturation coverage of these π and τ molecules amounted to another 0.5× to 1× the V_O concentration throughout our experiments. This either means that some of the molecules are in a superoxo charge state, or that additional electrons are provided by the bulk dopants. In our calculations, adding another O_2 molecule to the slabs shown in Fig. 1 does not result in chemisorption; the excess electrons provided by the oxygen vacancy are already consumed by the first peroxo species. Doping the slab by including extra electrons, in addition to the existing ones, allows further chemisorption of molecules, see Fig. SM2.

In Fig. 2 we investigated the adsorption configurations of superoxo species. The superoxo species were formed by co-adsorbing two molecules in configurations corresponding to a peroxo charge state to the slab containing one V_O. The spin-projected DOS of the co-adsorbed pairs of molecules is now characterized by two empty spin-down in-gap states, one for each adsorbed molecule, while the populated spin-up states associated with the molecules are located within the valence band. Projected partial-charge-density plots associated with the spin-down, in-gap empty states are plotted at the right side of the panels in Figures 2a and 2b. These empty states have the symmetry of the antibonding $2\pi^*$ orbital and illustrate the spatial distribution of the filled spin-up $2\pi^*$ states at each molecule. The table in Fig. 2c quantifies the properties of the adsorbed superoxo species. The adsorption energy per molecule implies chemical bonding of the superoxo species, but in a metastable state at this level of theory, due to the weaker adsorption energies than single peroxo species adsorbed to the same slab. Bond lengths of the co-adsorbed molecules agree with the expected values for superoxo species (75), as do the Bader charges equal to one half of the Bader charges for the calculated peroxo species. Singly charged oxygen adatoms O^-_{ad} could not be stabilized employing the methods used to calculate the other peroxo and superoxo species (Figures 1–2), and we conclude that they are unstable or at least not preferable.

Comparison of the calculated and experimentally observed geometries of superoxo and peroxo ω and τ molecules indicates their charge state on the surface: Calculated superoxo ω and τ molecules have a rotational angle of 60° with respect to the O$_{br}$ rows, which does not correspond to the angles measured in the AFM images. On the other hand, the geometry of the calculated peroxo ω and τ molecules does correspond to the experimental observations: peroxo ω molecules are perpendicular to the O$_{br}$ row, and the peroxo τ molecules are rotated towards the O$_{br}$ row by 45° (more detailed comparison in Fig. SM3). Therefore, we assign the ω and τ molecules to the energetically more favorable peroxo ω^{2-} and τ^{2-} states. The calculated geometry of the superoxo and peroxo π molecules differ only in the bond length, by values too small for the resolution of the AFM images (limited by the convolution of the tip apex shape and the shape of the adsorbate). Experimentally, we do not observe a preference for either the π or τ molecules, which indicates their similar adsorption energies. Therefore, we must assume that the π molecules are adsorbed in the energetically favored peroxo π^{2-} state as well. The geometry of the oxygen adatoms cannot be used to determine their charge state in a similar manner as the ω and τ molecules. According to calculations, doubly ionized singlet O^{2-}_{ad} is the only stable species, hence we assign the charge of oxygen adatoms accordingly. The absence of theoretically metastable superoxo species on the surface exposed to 0.5 L of O_2 at the temperature of 80 K (Fig. 1b) implies that, once the peroxo species is adsorbed, it will not share charge with the next molecule that arrives to the surface. Furthermore, the calculated adsorption energies of the peroxo and superoxo species (Figures 1h and 2c) show that if the co-adsorption of two superoxo species were to occur in our experiments, it is energetically favorable for one superoxo molecule to donate an electron to the other one and subsequently desorb, resulting in a surface with one adsorbed peroxo O_2^{2-} species.

B. Annealing. Annealing of the surface reveals the gradual activation of various O_2 dissociation channels. Figures 3a–c show constant-height AFM images taken after exposing the sample to O_2 at 80 K, followed by annealing to different temperatures, and subsequent cooling to the measurement temperature of 80 K. The amount of adsorbed O_2 is close to the saturation coverage. The statistics in Fig. 3d were collected by counting the number of each species $N(x)|x \in \{\omega, \pi+\tau, O_{ad}\}$ in at least two representative 60 nm^2 images at each given temperature, and normalizing this number to the number of oxygen vacancies $N(V_O)$ on the respective images (error bars in the stacked bar graphs are equal to $\sqrt{N(V_O)}$). The histogram at each temperature is divided in two columns. The left column represents the total number of oxygen vacancies

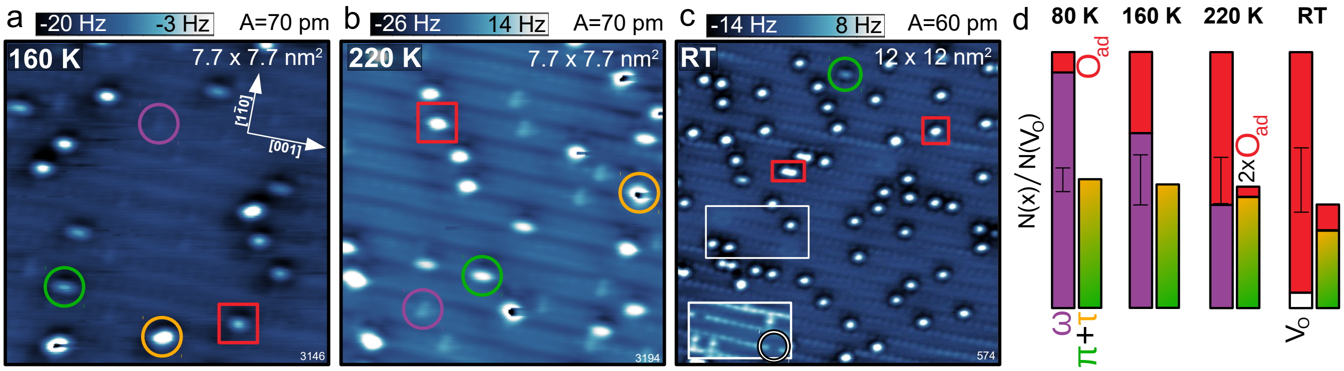


Fig. 3. Step-wise annealing of $TiO_2(110)$ with a close-to-saturation coverage of O_2 dosed at 80 K. AFM images (taken at 80 K) after annealing to a temperature of a) 160 K, b) 220 K, and c) room temperature (RT). The adsorbed species are marked with the same colors and symbols as in Fig. 1, with rectangles marking pairs of atomic O adatoms ($2{\times}O_{ad}$). The inset in (c) is an AFM image of the white rectangle imaged closer to the surface, showing an empty V_O more clearly. d) Number of adsorbed species $N(x)|x \in \{\omega, \pi+\tau, O_{ad}\}$ at each annealing temperature; both columns are normalized to the number of (empty and filled) oxygen vacancies $N(V_O)$ on the surface.

obtained as a sum of empty oxygen vacancies, ω molecules, and isolated O_{ad} atoms, which are the product of the well-known "vacancy-healing" dissociation channel (21, 29, 30, 45). The right column is the sum of the total number of π and τ molecules, and the number of O_{ad} pairs on the same Ti_{5c} row ($2{\times}O_{ad}$), which are the products of a dissociation channel along the Ti_{5c} rows (62), normalized to the concentration of oxygen vacancies as well. The observed, thermally induced reactions, together with the range at which their respective onset temperatures T_{min} fall, can be summarized as:

$$\begin{aligned}
\omega &\xrightarrow{+T} O_{ad} + O_{br} &;\quad & 10\text{ K} < T_{min} < 80\text{ K} \\
\pi &\xrightarrow{+T} 2 \times O_{ad} &;\quad & 160\text{ K} < T_{min} < 220\text{ K} \\
\tau &\xrightarrow{+T} 2 \times O_{ad} &;\quad & 160\text{ K} < T_{min} < 220\text{ K} \\
\omega &\xrightarrow{+T} O_2(\text{gas}) + V_O &;\quad & 220\text{ K} < T_{min} < 300\text{ K}
\end{aligned} \qquad [1]$$

There is no spontaneous appearance of O_{ad} after dosing O_2 at 10 K (the O_{ad} pair on Fig. 1a comes from deliberate O_2/Ti_{5c} dissociation), while the surface exposed to O_2 at 80 K (Fig. 1b) does show a small concentration of isolated O_{ad}. Dissociation of the ω molecules, which heals the oxygen vacancy and leaves an isolated O_{ad}, is therefore active at temperatures below 80 K. This dissociation channel is further promoted by thermal annealing, and already at 160 K the concentration of of ω molecules has notably decreased, followed by a proportional increase of the O_{ad} coverage. This trend continues through the 220 K temperature and no ω molecules are left after room temperature (RT) annealing. Most of them dissociated with the resulting concentration of isolated O_{ad} close to the initial concentration of oxygen vacancies. Additionally, a small fraction of oxygen vacancies reappear empty, indicating a possible weak desorption channel of ω molecules to the gas phase (O_2(gas)). Empty V_Os were never observed straight after dosing 0.5 L of O_2 at 80 K.

The dissociation of π or τ molecules through the dissociation channel along the Ti_{5c} rows becomes active above 160 K. After annealing the surface to 220 K, O_{ad} pairs appear. With increasing temperature up to RT, their concentration continues to increase at the expense of the π or τ molecules. Both π and τ molecules are still present on the surfaces after RT annealing, indicating a higher activation energy for dissociation compared to the ω molecules.

C. UV irradiation. Fig. 4 shows the effect of UV light irradiation on the surface exposed to O_2 at 80 K. The wavelength of the incoming light is sufficient to overcome the 3 eV band gap of TiO_2 and generate electrons and holes responsible for the observed photochemistry. Fig. 4a is the starting point of this experiment. The highlighted species in Fig. 4a are a guide to the eye for following the reactions after a low dose of UV irradiation (20 W for 20 s), resulting in the surface shown in Fig. 4b. The oxygen adatoms are unaffected by UV irradiation irrespective of the dose, and provide reference patterns (red squares in Fig. 4) for locating the same region on the surface after the UV irradiation. Following the evolution of the highlighted molecular species from Fig. 4a to Fig. 4b reveals that very few ω molecules dissociated and left one adatom right next to the now-healed vacancy. Dissociation of π and τ molecules was not observed. They either remained unaffected, switched the configuration between each other, or molecularly desorbed (marked by diamonds in Fig. 4b). The observed reactions under the first UV dose of 20 W can be summarized as:

$$\begin{aligned}
\omega &\xrightarrow{UV} O_{ad} + O_{br} \\
\pi &\xrightarrow{UV} O_2(\text{gas}) \\
\pi &\xrightarrow{UV} \tau \\
\tau &\xrightarrow{UV} O_2(\text{gas}) \\
\tau &\xrightarrow{UV} \pi
\end{aligned} \qquad [2]$$

Applying an additional UV dose of 80 W for 20 s has a stronger impact on the adsorbed O_2, see the transition from Fig. 4c to 4d. All π and τ molecules desorbed (with the exception of a single τ molecule per 121 nm^2 of the surface; image not shown). Therefore, molecular desorption is the end product of O_2/Ti_{5c} photochemistry. On the other hand, the ω molecules started desorbing as well under increased UV dose:

$$\omega \xrightarrow{UV} O_2(\text{gas}) \qquad [3]$$

Most of the ω molecules still either remained adsorbed or dissociated, similar to their behavior under a small UV dose. The process of molecular desorption of ω molecules

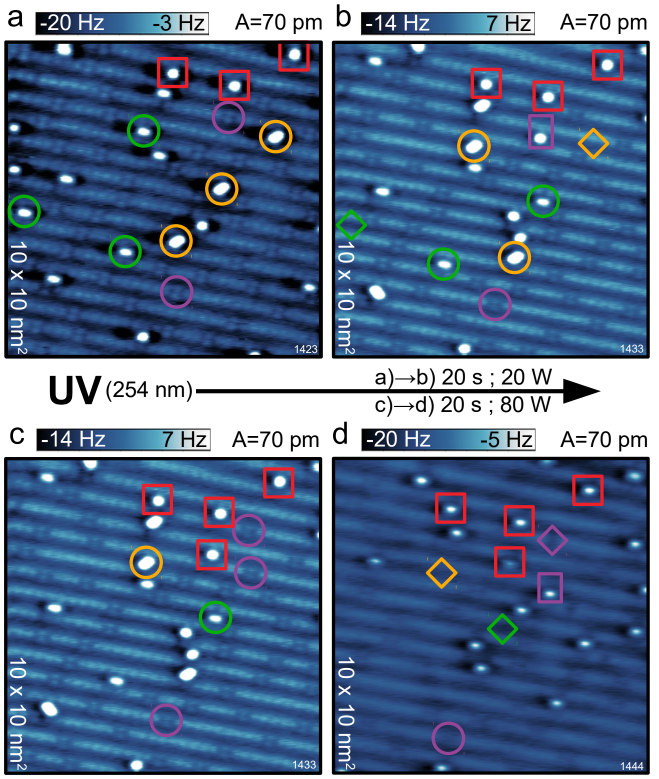


Fig. 4. Effect of UV light irradiation. a) AFM image of the surface after O_2 exposure at 80 K. The adsorbed species are marked with the same colors and symbols as in Fig. 1. b) The same region as in a) after 20 W UV irradiation for 20 s. The comparison of highlighted species in a) and b) reveals the reactions after the low UV dose. Diamonds mark molecular desorption, rectangles mark dissociation. c) The same image as b) but with different adsorbates highlighted. d) The same region as in b,c) after additional 80 W UV irradiation for 20 s. The comparison of highlighted species in c) and d) reveals the reactions after the increased UV dose.

under UV illumination demonstrates a lower cross section than the desorption of π or τ molecules, and constitutes a "slow" desorption channel, which has been reported to be active for even larger UV photon doses (39). Thus, the end product of O_2 photochemistry is a surface with no molecular species adsorbed, but a rather clean surface with a few oxygen vacancies and adatoms.

D. Tip-induced dissociation and desorption. Fig. 5 shows dissociation events induced by electron injection. The AFM image in Fig. 5a shows the O_2-covered surface at 80 K. Applying a +3.0 V sample bias pulse over a point on this surface dissociates most of the molecules, as revealed by the AFM image in Fig. 5b. These two figures illustrate the difficulties of studying this adsorption scenario using STM alone: Besides dissociating the molecules, submolecular resolution in STM is extremely rare and can be obtained only in immediate proximity to the surface where the tip flexibility contributes to the contrast (76–78) - see the constant current STM image shown in Fig. SM4. Molecular species were also deliberately dissociated in a more controlled fashion, Figures 5c–e, by ramping the sample bias voltage in the *positive* direction. When the tip-sample bias is ramped in a certain range, the underlying adsorbate can experience a change due to the tunneling from the tip to the unoccupied states of the adsorbate. This changes the frequency shift vs. bias curve (Kelvin parabola) (79) above the adsorbate due to the changed electrostatic forces acting on the tip $\left(\mathrm{O}_2^{2-} \rightarrow 2 \times \mathrm{O}^{2-}\right)$. Taking AFM images before and after the positive sample bias ramps confirms that all molecular adsorbates can dissociate. The characteristic bias necessary for dissociation varies for different species: ω molecules typically dissociate at a bias of +1.25 V (Fig. 5c), π molecules at a bias of +0.3 to +0.5 V (Fig. 5d), and the τ molecules above +3.0 V (Fig. 5e). We observed that τ molecules can either rotate (Fig. 5e top) or dissociate (Fig. 5e bottom) at bias voltages close to +3.0 V, and several consecutive rotations can be seen in Fig. SM5.

Fig. 6 shows desorption events of all three species, induced by *negative* sample bias ramps. In this case, electrons are removed (holes are injected) directly above the adsorbed molecules, leading to their desorption. The hole-induced desorption of oxygen is a well-accepted scenario (42, 48), so we did not perform extensive systematic experiments in this direction. Additionally, the desorbing molecule has a high probability of readsorbing at the tip apex, thus destroying the tip functionalization. Therefore, these desorption experiments were performed with the tip retracted 2 Å from the surface and we only present data where the resulting frequency shift vs. bias curves did not show any changes before and after desorption. The bias was ramped down to a minimum of -3.0 V for desorption of ω and τ molecules (between Fig. 6a and Fig. 6b) and down to a minimum of -2.0 V for desorption of the π molecules (between Fig. 6b and Fig. 6c).

The STM-induced events are qualitatively similar to the UV-induced events (electron-induced dissociation and hole-induced desorption), but there are differences between the two approaches. The configuration switch between π and τ molecules and vice versa was never achieved using the STM tip.

E. Force-distance curves. All AFM images shown in this paper were measured with the same tip functionalization. This tip consistently displays a characteristic contrast over the adsorbed O_2 molecules, and also provides excellent resolution of the oxygen sublattice of the substrate. In order to better understand this unique tip functionalization, we measured force-distance curves above all the species, and compared them to DFT+U calculations.

Fig. 7a shows the experimentally measured force-distance $F(z)$ curves above all surface species. The positions of the minima in the $F(z)$ curves are indicative of the relative heights of the different adsorbed species: The τ molecule is the highest one, followed by the O_{ad} and the π molecule, while the lowest-lying ω molecule lies in-plane with the O_{br} rows (taken as zero in the z-scale in Fig. 7). Fig. 7b compares the minima of the experimental $F(z)$ curves (left), with the vertical heights of the molecules corresponding to the relaxed slabs in Figures 1–2 (right).

The maximum of the experimentally measured attractive forces above the species are in the order of tens of pN, *i.e.*, the curves were obtained by a chemically inert tip. This is consistent with the oxygen-terminated TiO_2 tip apex obtained by our purposeful tip functionalization. Therefore, we used an oxygen-terminated $(\mathrm{TiO}_2)_5$ cluster tip (inset of Fig. 7c), developed in previous works (80–82) to explicitly simulate the obtained force-distance curves. These calculated $F(z)$ curves are plotted in Fig. 7c and the setup for calculating the $F(z)$

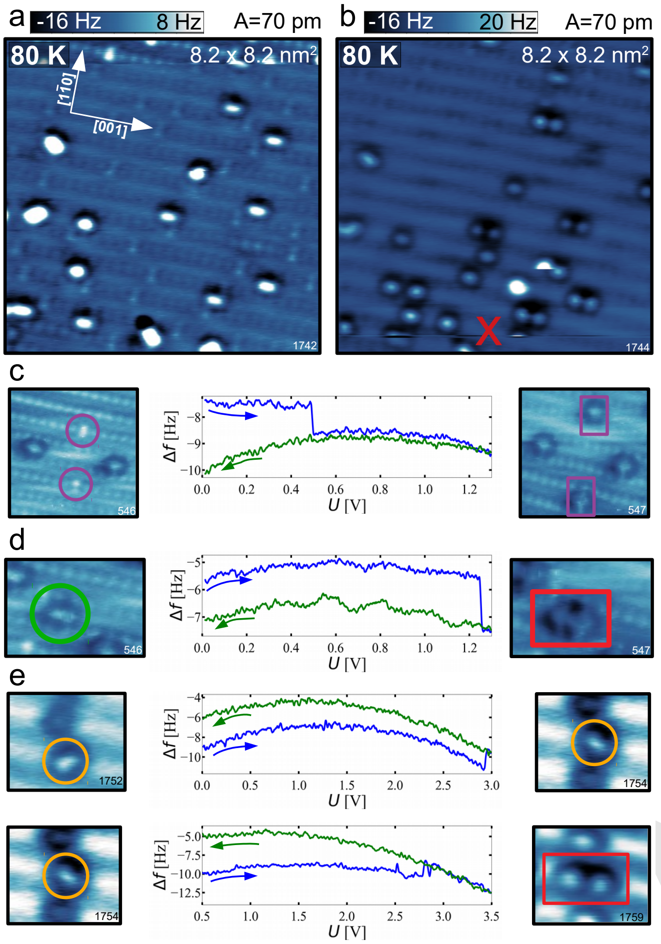


Fig. 5. Tip-induced dissociation a) AFM image of the O_2-covered surface b) AFM image of the same area as in (a), after a +3 V bias pulse at the spot marked by the red "x". c–e) AFM images of the ω, π, and τ molecules respectively, before (left) and after (right) tip-induced dissociation. The frequency shift vs. bias voltage graphs, showing the forward and backward bias ramp, are shown in the center of the panels. The τ molecule shown in panel (e) was observed to either rotate (top) or dissociate (bottom).

curves is explained in more detail in Fig. SM6. Movies of the simulated tip approach are available online as a supplement.

In Fig. 7d, we constructed a simulated constant-height AFM image of the surface using only the simulated $F(z)$ curves in Fig. 7c, and the geometries of the adsorbed species from Figures 1c–g. Two-dimensional maps of the force above the O_2-covered surface at different heights were constructed by calculating the pair-wise interaction between each of the constituent atoms of the surface and the adsorbates, with the O terminated apex of the tip. The force maps within the range of heights spanned by the oscillation amplitude A, $F(z \in [h-A, h+A])$, were converted to a constant-height frequency shift image $\Delta f(h = const.)$ at the distance of 2.6 Å from the O_{br}, by using the small oscillation amplitude approximation (83). The simulated frequency shift is larger by a factor of 5 when compared to the highly resolved experimental AFM images, because the DFT+U calculations overestimated the protrusion of each species (Figures 7b–c); the simulated tip had to approach closer to the surface in order to show repulsion above both the adsorbed and the lattice oxygen atoms.

The attractive interaction in the simulated $F(z)$ curves has a pure van der Waals character. When the van der Waals correction is switched off in the calculations, there is no attraction in the simulated $F(z)$ curves (see Fig. SM7). The imaging contrast is therefore based on a combination of electrostatic and Pauli repulsion between tip and surface O atoms. The absence of strong chemical interaction makes these tips easy to use and stable over long periods of time. We also simulated $F(z)$ curves with the same tip cluster but with different orientation with respect to the surface in order to increase the van der Waals attractive interaction. They are shown in Fig. SM8 and display deeper attraction minima.

2. Discussion

A. Adsorption and charge state of O_2. The key requirement to unambiguously observing the molecularly adsorbed oxygen species is measuring with AFM at zero sample bias, *i.e.*, with no charge injection into the molecules. Under these conditions, the ω molecule is clearly imaged as a two-atom feature within an O_{br} row, while the π and τ molecules are observed as two clearly distinct species. This allows us to clearly identify the geometries of O_2/V_O and O_2/Ti_{5c}, whose existence was previously inferred from the disappearance of the oxygen vacancies, or the appearance of faint feature on the Ti_{5c} rows after O_2 exposure, respectively, by using very delicate conditions in STM (45–49). With the unambiguous insight into the adsorption configurations, we can exclude some theoretically proposed adsorption configurations, and confirm the presence of theoretically proposed ω (50–56), π (51–54, 56), and τ (50–59) molecules only. Our work does not provide any indication of other proposed species, such as the tetraoxygen (84, 85).

The charge state of adsorbed O_2 molecules is a long-standing question in oxygen chemistry. Beside quantitative measures of the charge of the stable molecules in calculations (Figures 1h and 2c), we additionally assign their charge state through the clear charge transfer from the subsurface electronic polarons to the adsorbed molecules, seen by comparing the electronic structure prior and after the simulated O_2 adsorption. Within the scope of DFT+U calculations presented here, both superoxo species are metastable with respect to the peroxo species. The imaging setup used in this work provides little direct information on this topic, but comparison of the calculated and measured adsorption geometries strongly support the peroxo charge state for all adsorbed molecules. There is no significant variation in the apparent height or adsorption geometry between adatoms or molecules of the same type.

When comparing the thermodynamical stability of the superoxo and peroxo species, none of the superoxo adsorbed species would be preferred to the adsorbed peroxo O_2. Our calculations show that, out of all combinations, only two superoxo τ molecules would be preferred to one peroxo τ molecule, at extremely high O_2 chemical potentials, above -0.1 eV, which corresponds to temperatures below 150 K and pressures above 10 bar. However, even this preference is lost because it is energetically downhill to convert two superoxo τ molecules into one peroxo π molecule and one gas molecule.

The calculated adsorption energies of the peroxo species are -1.17 and -1.53 eV for the τ and π molecules, respectively, which is consistent with the desorption peak found in TPD at ≈400 K (31–33, 37, 39). The adsorption energy corresponding to the TPD data is between 1.0 to 1.2 eV, close to our calculated

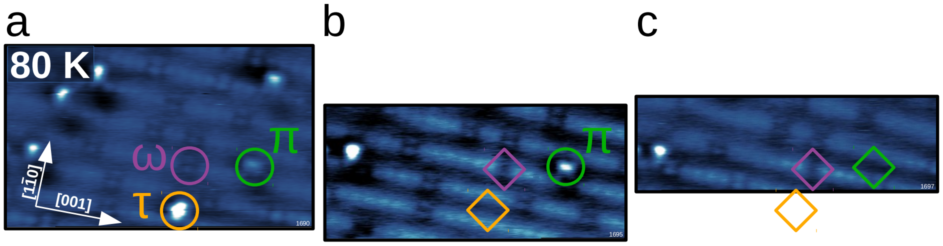


Fig. 6. Tip-induced desorption a) AFM image of the O_2-covered surface. b) AFM image of the same region after negative bias was ramped above the ω and τ molecules causing their desorption. c) AFM image of the same region after negative bias was ramped above the π molecule causing its desorption.

values. It is important to consider the chemical potential of an electron when comparing the TPD data with the energies obtained via DFT: Electrons donated by oxygen vacancies lie very close to the conduction band in DFT calculations, while the experimental Fermi level is typically 0.2 to 0.3 eV lower due to the band bending induced by the adsorbed oxygen (86). The experimental adsorption energies may be therefore lower by 2× the value of the band bending (2× for the peroxo charge state), which provides a reasonable match for both the τ and π molecules in the peroxo configuration.

Assuming that all the molecular species are in the peroxo charge state, the ω molecules use all excess charge provided by the surface oxygen vacancies, while the other chemisorbed species must drain electrons from subsurface dopants, *i.e.* interstitial Ti atoms (28, 62, 87) or bulk oxygen vacancies (88). They donate electrons for further chemisorption of π and τ molecules dosed at 80 K, up to a saturation coverage of 0.5 to 1 per oxygen vacancy. It is noteworthy that all the molecular species are oriented parallel to the surface, making them hard to detect in infrared absorption techniques (89). Also, their peroxo state makes them undetectable by electron paramagnetic resonance (90). Electron energy loss spectroscopy measurements on O_2-exposed rutile $TiO_2(110)$ surfaces support the peroxo charge state assignment (49).

B. Thermally activated processes. Our results show that the vacancy-mediated dissociation channel (21, 29, 30, 41) - the dissociation of ω molecules - becomes active at temperatures around 80 K. The dissociation channel of τ and π molecules along Ti_{5c} rows (23, 26, 30, 47) is activated above 160 K. Our images of the O_2-covered surface at 80 K generally show lower concentrations of isolated oxygen adatoms compared to previous STM works (21, 23, 28–31, 45–49), mainly due to the prevention of artificial, STM-induced dissociation. The large temperature range of the dissociation events indicates that the process is limited by availability of electrons rather than thermal barriers for dissociation; the dissociation reactions require excess electrons from the substrate:

$$\begin{aligned}
\omega^{2-} + 2e^- &\rightarrow O_{ad}^{2-} + O_{br}^{2-} \\
\pi^{2-} + 2e^- &\rightarrow 2 \times O_{ad}^{2-} \\
\tau^{2-} + 2e^- &\rightarrow 2 \times O_{ad}^{2-}
\end{aligned} \qquad [4]$$

Each of the thermally activated dissociation reactions drains electrons from the bulk and localizes them at the adsorbed oxygen adatoms. This increases the upwards band bending (79) near the surface and makes every further reaction more difficult. The band bending may be counteracted first by thermal excitations of electrons closest to the Fermi level and at higher temperatures by slow diffusion of titanium interstitials Ti_{int} (28, 33, 62, 87) or bulk oxygen vacancies (88) towards the surface.

It is surprising that some of the oxygen vacancies become empty after annealing (see Fig. 3c), which was also apparent in previous STM studies (31). This indicates competition for electrons at elevated temperatures even between the co-adsorbed species. One can consider a case where the excess electrons for dissociating π or τ molecules come from an ω molecule co-adsorbed at the surface, leading to its desorption. The energy balance calculated in Fig. 1h indicates that such process could be energetically feasible, while a sole desorption of the ω molecule is unlikely.

C. UV-induced reactions. It is well-established that the UV-induced O_2 dissociation is an electron-induced process, while holes induce O_2 desorption (11, 13, 14, 36, 38, 40, 41, 43, 48, 49, 91). For our system, this scenario has been verified by tip-induced electron and hole injection as shown Figures 5 and 6. Events observed upon UV irradiation have a similar base, but there are differences. First, in STM-induced events we can control the potential, but not the number of electrons. Second, the coupled electron and hole dynamics occurring under UV illumination is not reflected in the tip-induced events.

Our UV irradiation experiments show that the ω molecules are predominantly active for dissociation, while the π and τ species prefer desorption. This can be related to the fact that the π and τ species have an in-gap state (Fig. 1), which allows them to accept thermalized holes. Additionally, they are negatively charges species, electrostatically attracting the holes. This is not the case for the ω species: the original oxygen vacancy is 2+ while the ω molecule is 2-. In other words, the charge of the ω molecule is the same as that of the O_{br} atom that it replaces. Together with the absence of an in-gap state, this results in a preference of ω molecules to electron-mediated events.

Let us now discuss whether the UV-induced photodesorption of O_2 is a one-hole or a two-hole process. Previously, this question was addressed by changing the UV intensity, which changes the hole concentration $[h^+]$; a desorption rate linear (square) in $[h^+]$ indicates a one-hole (two-hole) process (37–39). A one-hole process was suggested based on these measurements, which was taken as an indication of superoxo species present at the surface (37–43). Our insights on the atomic-level mechanisms indicate that this is not necessarily the case.

We attribute the long tail of desorbing molecules after prolonged UV irradiation (37–39) to the slow desorption of ω molecules. This very low desorption rate makes it difficult to measure the dependence of desorbed ω molecules on the incoming light flux (37–39), and it is consistent with the low cross-section of ω molecules for accepting simultaneously two holes:

$$\omega^{2-} + 2h^{+} \rightarrow \mathrm{O_2(gas)}$$

We observed that the fast initial desorption under UV irradiation (37–39) is due to the desorption of π and τ molecules. Moreover, our data in Fig. 4b indicate that the switching between the π and τ molecules is at least as frequent as their desorption at small UV exposures. We propose that a metastable transition state is responsible for this configuration switching. After accepting one hole, a π or τ molecule is transformed into a metastable superoxo species on the $\mathrm{Ti_{5c}}$ row ($\mathrm{O_2^-/Ti_{5c}}$):

$$\left(\pi^{2-} \text{ or } \tau^{2-}\right) + h^{+} \rightarrow \mathrm{O_2^-/Ti_{5c}} \qquad [5]$$

This metastable state can either desorb in several ways, or revert to the peroxo state with the addition of one electron from the surface. Thermal desorption of metastable superoxo species with a calculated adsorption energy of $E_{\mathrm{ads}} \approx$-0.7 eV is unlikely at the temperature of 80 K in our experiments. We also note that disproportionation, *i.e.* converting two metastable superoxo molecules into one peroxo molecule and an additional gas molecule, is based on a one-hole process, but the reaction rate would still be proportional to $[\mathrm{h}^+]^2$ like a two-hole process, which does not agree with the literature (37–39).

A possible one-step one-hole desorption process would be that the metastable superoxo desorbs due to the kinetic energy it gains in the transition from the peroxo state:

$$\mathrm{O_2^-/Ti_{5c}} + E_{\mathrm{kin}} \rightarrow \mathrm{O_2(gas)} + \mathrm{e}^- \qquad [6]$$

This process is more likely for τ molecules than for π molecules, because the adsorption geometry of π^{2-} and π^- is very similar, while the adsorption geometry of τ^{2-} and τ^- significantly differ in both in the rotational angle and height (Fig. 7b).

We consider a two-step two-hole desorption channel of the π^{2-} and τ^{2-} molecules more likely. Under UV irradiation, both electrons and holes are generated. This enables both, the hole-induced desorption and the electron-induced readsorption of the metastable superoxo state:

$$\begin{aligned} &\mathrm{O_2^-/Ti_{5c}} + h^{+} \rightarrow \mathrm{O_2(gas)} \\ &\mathrm{O_2^-/Ti_{5c}} + e^{-} \rightarrow \pi^{2-} \text{ or } \tau^{2-} \end{aligned} \qquad [7]$$

Our data on switching between τ and π configurations indicate that these two processes happen with similar probabilities, and more detailed examples are shown in Fig. SM9. Assuming the concentrations of UV-generated electrons and holes are proportional to each other, the branching ratio of these desorption and readsorption processes will be constant. Therefore, the desorption rate will depend only on the probability of the initial peroxo to metastable superoxo transition, and the branching ratio. Although we have a two-hole process, the desorption rate is thus proportional to the hole concentration $[\mathrm{h}^+]$ and not its square. Within this model, the desorption rate of τ and π molecules would be proportional to $[\mathrm{h}^+]^2$ only if the $\mathrm{O_2}$-covered surface were n-doped and in the absence of upward bend bending, *i.e.* for a constant electron concentration not depending on the UV intensity. This assumption would, however, lead to a modification of the analysis in (37–39) resulting in a desorption rate proportional to $[\mathrm{h}^+]^{\frac{1}{2}}$, which is unlikely. Therefore, our peroxo assignment of the adsorbed $\mathrm{O_2}$ is consistent with the data of (37–39).

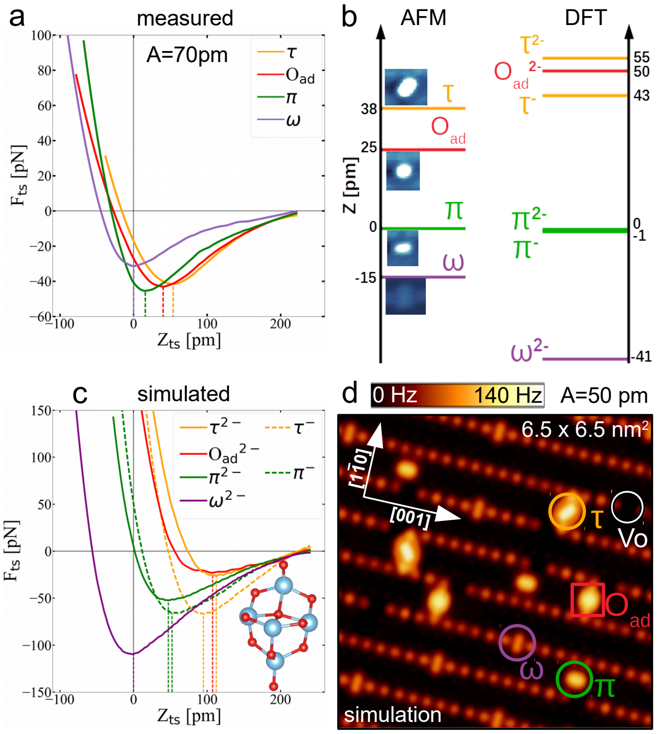


Fig. 7. Height of the adsorbed species. a) Experimental force-distance $F_{\mathrm{ts}}(z)$ curves obtained above each of the adsorbates. b) Comparison of the measured height (minimum of $F_{\mathrm{ts}}(z)$, left) and calculated height (right) of the adsorbed species. c) Simulated $F_{\mathrm{ts}}(z)$ curves obtained with an non-reactive O terminated $(\mathrm{TiO_2})_5$ tip, illustrated in the inset d) Simulated constant-height AFM image constructed by the simulated tip-sample forces seen in (c).

D. AFM imaging mechanism. An important aspect of this work is the AFM imaging with an O-terminated tip. Purposely functionalized tips play a major role for non-contact AFM, and our tip termination results in the exceptional resolution and offers many opportunities for the future. The key aspects of this tip termination are its inert character towards the surface oxygen atoms, high stability (it works well for measurements performed at 80 K), and rigid character with respect to lateral bending. When applying the traditional CO-terminated tips to $\mathrm{TiO_2}$ surfaces, we had difficulties with their stronger attractive interaction with surface atoms, and low stability during measurements performed at 80 K. Also, the lateral bending of the CO (64, 65), which is the key requirement for submolecular imaging of organic molecules (16), is not helpful on ionic surfaces; it distorts the image and creates artificial lines connecting neighboring anions.

We used the tips prepared on the $\mathrm{O_2}$-$\mathrm{TiO_2}$ system for imaging other metal oxides, with a significant success – see images of $\mathrm{In_2O_3}$ (92–94) in Fig. SM10 as an example. Oxygen-terminated tips have also been reported to be successful in imaging CuO thin films (95, 96). The main obstacle is the difficulty to functionalize the tip in the desired way. We were unable to obtain this functionalization on clean TiO_2 surfaces; the oxygen could only be picked from a chemisorbed O_2 molecule by dissociating it by a positive sample bias voltage pulse, while the tip is close enough to "catch" one of the O atoms, while the other remains on the surface. On the other hand, the data reported on CuO thin films indicate easy functionalization. It is likely that the enthalpy of oxide formation (97) plays a role here – it is energetically expensive to extract a single atom from the TiO_2 lattice, while the energy cost on copper oxide is much lower.

3. Summary and conclusions

We identified all adsorption configurations of molecular O_2 species observed on the rutile $TiO_2(110)$ surface. This was made possible through the use of non-intrusive nc-AFM imaging, which reveals the true adsorption geometry without interfering with the surface. Three molecular O_2 species were observed: two adsorbed on the Ti_{5c} rows, and one adsorbed in the oxygen vacancy. Oxygen atoms sitting above Ti_{5c} atoms are a result of the molecular dissociation through two dissociation channels: vacancy-assisted dissociation with an onset temperature below 80 K and dissociation of molecules on the Ti_{5c} rows above 160 K. At room temperature, no molecules are left inside oxygen vacancies, but some remain on the Ti_{5c} rows, giving rise to the TPD peak around 400 K. The adsorption was simulated using DFT+U on a reduced slab and all the molecular adsorbates were assigned to be peroxo O_2^{2-}, while the adatoms are doubly ionized O_{ad}^{2-}. The calculations show charge transfer from the polaron-hosting Ti_{6c} sites to the adsorbed oxygen species followed by a change or complete disappearance of the in-gap state characterizing a reduced slab with oxygen vacancies. O_2/Ti_{5c} molecules prefer photodesorption under UV irradiation, while O_2/V_O mostly dissociate under the same conditions. We confirm that the dissociation of O_2 is electron-mediated, while desorption is a hole-mediated process, by injecting or removing electrons using an STM tip. Within our model, the desorption of O_2/Ti_{5c} is either a one-step one-hole process, where the single hole can desorb a peroxo molecule, or a two-step two-hole process with an intermediate, metastable superoxo state. The clear imaging contrast in AFM images is due to the use of passivated O-terminated tips. We confirm that the small attractive force between the tip and the adsorbates has a purely van der Waals character. This type of tip termination shows promise for further studies of oxide surfaces.

Methods

The experiments were performed in a UHV chamber with a base pressure below 2×10^{-11} mbar, equipped with a custom-modified Omicron qPlus LT head. Measurements were performed using qPlus sensors with a separate channel for the tunneling current (98). The deflection signal was measured with a cryogenic differential in-vacuum preamplifier (99). Electrochemically etched tungsten tips were glued to the tuning fork and cleaned by field emission and self-sputtering in 2×10^{-6} mbar Ar^+ (100). The tips were treated by controlled touching of the rutile $TiO_2(110)$ surface, and subsequently functionalized with an oxygen at the tip apex by applying voltage pulses above the adsorbed O_2 molecules. The rutile TiO_2 sample was cleaned by cycles of 1.5 keV, Ar^+ ion sputtering (10 min, 1 μAcm^{-2}), followed by annealing up to 970 K in ultra-high vacuum (UHV). The clean surface was inspected with AFM and STM and revealed a (1 × 1) termination with V_Os with a density ranging from 5–12%. Molecular O_2 (99.99%) was dosed at 10 K or 80 K by back filling the chamber with a leak valve, and the measurements were performed at liquid helium (LHe) and liquid nitrogen (LN_2) temperatures, respectively. We note that the crystal is insulating at 4.8 K. Ultraviolet light (UV) from a standard Hg source (254 nm) was directed to the sample at LN_2 temperature through a quartz window, after the tip was sufficiently moved to prevent shadowing of the incoming light. A lamp power of 20 W in the UV irradiation experiments corresponds to a photon flux of roughly 1×10^{15} cm^{-2}s^{-1}.

The density functional theory (DFT) calculations were performed with the Vienna *Ab initio* Simulation Package (VASP) (101, 102) and employed the generalized gradient approximation (GGA) within the Perdew, Burke, and Ernzerhof parametrization (103, 104). The van der Waals interactions were included as proposed by Dion *et. al.* (105). The Ti 3*d* orbitals were treated with an on-site effective U (106) of 3.9 eV, previously determined by constrained-random-phase calculations on bulk rutile titania (66).

The $TiO_2(110)$ surface was modeled by constructing a 6×2 slab with 5 TiO_2 layers. The bottom two layers were kept fixed, while the top three layers were relaxed with a convergence criterion of 0.01 eV/Å, using an energy cut-off for the plane-wave basis set of 400 eV and a reciprocal-space sampling at the Γ point only. The adsorption energies of molecular $E_{\mathrm{ads}}^{\mathrm{O_2}}$ and atomic $E_{\mathrm{ads}}^{\mathrm{O}}$ oxygen species were calculated as

$$E_{\mathrm{ads}}^{\mathrm{O_2(O)}} = E_{\mathrm{TiO_2+O_2(O)}} - (E_{\mathrm{TiO_2}} + E_{\mathrm{O_2(O_2/2)}}) \quad ,$$

where $E_{\mathrm{TiO_2}}$ is the total energy of the minimum energy, polaron-hosting ground state of the clean slab reduced by one V_O, $E_{\mathrm{TiO_2+O_2(O)}}$ is the total energy of the surface slab with the adsorbed molecular (atomic) oxygen, and $E_{\mathrm{O_2(O_2/2)}}$ term represents the energy of the O_2 molecule (half the energy of the molecule when calculating adsorption energy of the adatom) in the gas phase.

Experimental frequency shift vs. distance curves were averaged over at least five curves and transformed to force-distance curves with the Sader inversion equation (107). The long-range background was estimated by measuring $F(z)$ curves above the Ti_{5c} rows and subtracted from the experimental curves. The simulated force curves were obtained by explicitly including an oxygen terminated $(TiO_2)_5$ tip cluster (80–82) in a 34 Å thick vacuum region above the surface and performing accurate DFT calculations above each adsorbed species, with an approach step size of 25 pm. The bottom five atoms of the tip cluster, together with the top three layers of the surface slab, were relaxed with a more stringent relaxation convergence criterion of 0.005 eV/Å.

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