

# Tunneling Desorption of Single Hydrogen on the Surface of Titanium Dioxide

*Taketoshi Minato*<sup>\*,†,‡,○</sup>, *Seiji Kajita*<sup>\*,§,◇</sup>, *Chi-Lun Pang*<sup>||</sup>, *Naoki Asao*<sup>⊥</sup>,  
*Yoshinori Yamamoto*<sup>⊥</sup>, *Takashi Nakayama*<sup>§</sup>, *Maki Kawai*<sup>\*,#</sup> and *Yousoo Kim*<sup>\*,‡</sup>

<sup>†</sup>International Advanced Research and Education Organization, Tohoku University, Sendai 980-8578, Japan.

<sup>‡</sup>Surface and Interface Science Laboratory, RIKEN, 2-1 Hirosawa, Saitama 351-0198, Japan.

<sup>§</sup>Department of Physics, Chiba University, 1-33 Yayoi, Inage, Chiba 263-8522, Japan.

<sup>||</sup>Department of Chemistry, University College London, London WC1H 0AJ, United Kingdom.

<sup>⊥</sup>WPI Advanced Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan.

<sup>#</sup>Department of Advanced Materials Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan.

<sup>○</sup>Present address: T.M.: Office of Society-Academia Collaboration for Innovation, Kyoto University, Uji-shi, Kyoto 611-0011, Japan, <sup>◇</sup>Toyota Central R&D Labs., Inc. 41-1, Yokomichi, Nagakute Aichi 480-1192, Japan.

**Corresponding Author**

[minato.taketoshi.5x@kyoto-u.ac.jp](mailto:minato.taketoshi.5x@kyoto-u.ac.jp) (T. M.), [fine-controller@mosk.tytlabs.co.jp](mailto:fine-controller@mosk.tytlabs.co.jp) (S. K),  
[maki@k.u-tokyo.ac.jp](mailto:maki@k.u-tokyo.ac.jp) (M. K.), [ykim@riken.jp](mailto:ykim@riken.jp) (Y. K.).

## **ABSTRACT**

We investigated the reaction mechanism of the desorption of single hydrogen from a titanium dioxide surface excited by the tip of a scanning tunneling microscope (STM). Analysis of the desorption yield, in combination with theoretical calculations, indicates the crucial role played by the applied electric field. Instead of facilitating desorption by reducing the barrier height, the applied electric field causes a reduction in the barrier width, which, when coupled with the electron excitation induced by the STM tip, leads to the tunneling desorption of the hydrogen. A significant reduction in the desorption yield was observed when deuterium was used instead of hydrogen, providing further support for the tunneling-desorption mechanism.

## **KEYWORDS**

defect, manipulation, scanning tunneling microscopy, titanium dioxide

Electric conductivity, photo physical properties, magnetic properties and catalytic activity can be produced by introduction of defects onto inert materials.<sup>1-8</sup> Clarifying the fundamental properties of such defects is therefore of extraordinary interest in developing new materials. Typical defects on titanium dioxide (TiO<sub>2</sub>) include hydrogen (H) adatoms, oxygen vacancies (O<sub>vac</sub>) and Ti interstitials, each of which confer new properties absent in the perfect material. TiO<sub>2</sub> is a transition metal oxide showing a number of characteristic functions that can be exploited in processes such as heterogeneous catalysis, photocatalysis, sensing, and light-induced switching, amongst others.<sup>1-10</sup>

Defects have been created at TiO<sub>2</sub> surfaces by thermal annealing<sup>11</sup> as well as by photo- and electron-stimulated desorption (PSD and ESD).<sup>1, 12, 13</sup> The principles of these methods are based on thermal reaction to produce O<sub>2</sub> in the former case and inter-ionic Auger decay processes in the latter two examples.<sup>1, 11-13</sup> While these methods have been successfully used to introduce defects on the TiO<sub>2</sub> surface, precise control of the defect arrangement is not possible. The control of the defect arrangement on TiO<sub>2</sub> has been reported by applying specific voltages with a scanning tunneling microscope (STM). For example, Suzuki *et al.* found that hydrogen atoms on TiO<sub>2</sub> can be removed by scanning at a raised bias<sup>14</sup> and we have recently reported the introduction of an individual O<sub>vac</sub> by applying a single voltage pulse.<sup>15</sup> While manipulation of defects by STM methods allows for ideal spatial control of the defect, the mechanisms are still unclear.

In the manipulation of atoms/molecules by STM, the mechanisms can be categorized into electron excitation and non-electron excitation processes. In electron excitation reactions, tunneling electrons excite electronic states that are related to chemical bonds [1, electronic state excitation]<sup>16</sup> or vibrational states (including translational, rotational and conformational change states) to overcome reaction barriers by exciting reaction coordinate modes [2, vibrational state excitation]<sup>17-19</sup>. Also, heating by electrons causes reaction in electron

excitation [3, manipulation by local heating].<sup>20</sup> In non-electron excitation reactions, direct interaction between the STM tip and atoms/molecules by means of van der Waals/chemical forces [4, direct manipulation]<sup>21</sup> or electric field to reduce the height of the reaction barrier [5, electric field excitation]<sup>22-24</sup> have been utilized to manipulate atoms/molecules. Here, we provide insight into such reaction mechanisms for manipulation of defects on TiO<sub>2</sub> by using action spectroscopy measured by STM (STM-AS), whereby the response of a molecule is recorded as a function of applied bias voltage.<sup>16-19</sup> H desorption on TiO<sub>2</sub> was chosen as a model system because it is the simplest reaction. We found that H desorption induced by the STM is a tunneling reaction facilitated by the reduction of the barrier width by the applied electric field together with excitation by the tunneling electrons. Although tunneling reactions of atoms/molecules induced by STM tips are reported<sup>25, 26</sup>, this reaction mechanism whereby the barrier width is reduced by the applied electric field has not been observed previously. Apart from being an important reaction mechanism in other H/TiO<sub>2</sub> systems, such reaction mechanisms are also likely to be important in other atomic scale reactions as well.

## Results and Discussion

Fig. 1a shows a typical STM image of H on TiO<sub>2</sub>(110) obtained with sample bias ( $V_s$ ) = +1.5 V. The bright rows and the spot at the center of the image are the Ti ions and H on bridging oxygen ( $O_b$ ), respectively.<sup>1-8, 14, 15</sup> After applying a  $V_s = +1.7$  V pulse to the H for 1 sec., the spot corresponding to H disappeared due to desorption of H (Figure 1b). In contrast, no change occurred when voltage pulses were applied with negative sample bias (up to  $V_s = -5.0$  V). These observations are in line with previous reports.<sup>1-8, 14, 15, 27, 29</sup>

In order to investigate the reaction mechanism for H desorption, STM-AS was measured. When the tip was fixed at  $V_s = +1.0$  V and  $I_t = 0.02$  nA (with no additional tip displacement (TD = 0 nm)), the obtained spectrum showed two clear threshold energies at  $V_s$

= +1.4 and +1.7 V (blue, filled squares and curve in Figure 2a). Displacing the tip closer to the TiO<sub>2</sub> surface leads to a shift of the thresholds towards lower energy. For example, when the tip was moved towards the surface (TD = -0.04 nm), the threshold energies were shifted to  $V_s = +1.3$  and +1.6 V (green, filled triangles and curve in Figure 2a) and with further displacement of the tip to -0.10 nm, the threshold energies were also further shifted to  $V_s = +1.2$  and +1.5 V (purple, filled circles and curve in Figure 2a). Further shifts of the threshold energies were not observed for displacements of -0.14 and -0.20 nm (orange, filled squares and black, filled triangles in Figure 2a). In contrast, displacement of the tip away from the surface to +0.1 nm led to a shift of the threshold energy originally at  $V_s = +1.7$  V to  $V_s = +2.0$  V (red, filled circles and curve).<sup>30</sup> Figure 2b summarizes the threshold energy shifts as a function of tip displacement. Clearly, the shift of the threshold energies depends on the tip displacement (TD between +0.1 and -0.1 nm) with saturation of the shift in the closer region (TD less than -0.1 nm).

Based on our STM-AS results, we consider possible mechanisms for the voltage pulse-induced desorption of H: [1] electronic state excitation of reaction coordinate modes<sup>16</sup>, [2] multiple vibrational state excitation for overcoming the reaction barrier<sup>17-19, 25, 26</sup>, [3] thermal reaction caused by local heating<sup>20</sup>, [4] direct manipulation by means of van der Waals/chemical forces<sup>21</sup> and [5] electric field excitation for reduction of the reaction barrier.<sup>22-24</sup> To assess the possibility of electronic state excitation of anti-bonding states,  $dI/dV$  measurements were performed on H/TiO<sub>2</sub>(110) as a function of TD. No electronic states were observed in  $dI/dV$  curves that correspond with the threshold energies observed in STM-AS (Figure S1). Also, the shift of the threshold energies ( $\approx 3.0$  V/nm in -0.1 ~ +0.1 nm of TD) in STM-AS did not match with the shift in  $dI/dV$  spectra ( $\approx 6.0$  V/nm) that is caused by tip induced band bending (TIBB) (Figure S1). This implies that the reaction cannot be caused by electronic state excitation. Next, we consider the possibility of multiple vibrational excitation

to overcome the reaction barrier. From density functional theory (DFT) calculations, the energy barrier of H desorption was obtained as 3.7 eV (open circles in Figure 3). To overcome the reaction barrier by vibrational state excitation, multiple excitation is necessary (for example, the vibrational energy of stretching mode of OH on TiO<sub>2</sub>(110) is 0.457 eV (3690 cm<sup>-1</sup>)<sup>31</sup>). However, the tunneling current dependence of the reaction yield indicates a one-electron process (Figure S2). Therefore, this reaction cannot be explained by multiple vibrational state excitation.<sup>32</sup> In addition, the possibility of local heating and direct manipulation by means of van der Waals/chemical forces can be eliminated because the thermal energy is not changed by tip position and the van der Waals/chemical forces are not dependent on the applied electric field. Finally, the possibility of electric field excitation was considered. We estimated the electric field generated in our experimental condition by carrying out simulations using a tip-sample distance of 0.4 nm at  $V_s = +1.0$  V<sup>35</sup>, with the SEMTIP program developed by Feenstra.<sup>36</sup> The electric field for the threshold energies of the shifted region ( $-0.1 < TD < +0.1$  nm) was estimated to be 3.25 – 4.00 V/nm. However, the reaction barrier obtained by the DFT calculation under the electric field (3.6 eV at 4.5 V/nm; black, filled circles in Figure 3) is not lower than the thermal activation energy estimated from the Arrhenius equation using the experimental condition (0.15 - 0.19 eV at 78 K assuming that reaction rates and frequency factor are  $1 - 100$  s<sup>-1</sup> and  $1 \times 10^{12}$  s<sup>-1</sup>, respectively<sup>37</sup>). We conclude therefore that the reaction cannot be caused by electric field excitation. Based on the above discussion, we conclude that the reaction cannot be caused by any one of these excitation processes.

Then, how does this reaction proceed? From the calculated potential curve under an electric field, it was found that while the *height* of the reaction barrier does not change significantly, either side of the maximum point (i.e. the points indicated by red arrows in Figure 3) decreases as a result of the applied field. The energy gain in the potential curve is

caused by ionization of the desorbed H and variability of the valence state and bond distance of Ti and O in the applied electric field (supporting information 4). This means the barrier *width* is reduced by the electric field and this may open up a tunneling channel for the desorption of H. In addition to this, the tunneling electrons injected by the STM tip also excite the adsorbed hydrogen into electronic or vibrational states part way up the energy barrier at which point the barrier width is narrower, thereby further increasing the tunneling probability. From the calculation of potential curves with and without applied electric field, therefore it is suggested that STM tip-induced H desorption is caused by a H tunneling reaction (for the effects of the tip on the reaction barrier, see supporting information 5).

To test this tunneling desorption mechanism further, we used STM-AS to measure any isotope effect on the reaction yield. STM-AS of D desorption from TiO<sub>2</sub>(110) showed a significant decrease ( $\approx 10^{-4}$ ) in the reaction yield at  $V_s = +1.8$  V (black, filled square and curve in Figure 4a) compared with H desorption (blue, filled square and curve in Figure 4a). A theoretical model was used to quantitatively explain the isotopic shift of the tunneling desorption. H on the O<sub>b</sub> of TiO<sub>2</sub> is positively charged, the hydrogen being attached to the O site through a bond with some ionic character.<sup>37,38</sup> The hydrogen feels an electric potential  $-\alpha eEx$  from the STM tip when the sample voltage is positive, where  $\alpha$  is a constant showing the valency of hydrogen,  $e$  is the elementary charge,  $E$  is the electric field,  $x$  is the position of the hydrogen. We modeled the system as an energy-potential well represented by the potential curve shown in Figure S4. We assume that the hydrogen receives energy,  $\varepsilon$ , from the tunneling electrons flowing from the STM tip to the sample. Using the Wentzel–Kramers–Brillouin (WKB) approximation<sup>39</sup>, the tunneling probability for the hydrogen desorption denoted by  $T$  is expressed by

$$T = \exp \left\{ -\frac{8\pi\sqrt{2m}}{3heE} (V_0 - \varepsilon)^{\frac{3}{2}} \right\}, \quad (eq. 1)$$



where  $h$  is the Planck constant,  $m$  is the mass of hydrogen,  $V_0$  is the reaction barrier (for detail, see supporting information 6). Equation 1 gives the dependence of  $T$  on  $m$ , so that with the mass of D being twice that of H, the multiplier factor of the exponential will increase by  $\sqrt{2}$  given that the isotopic element does not change electronic properties such as  $V_0$ . Figure 4a shows the H desorption yield spectrum together with the same spectrum re-plotted with the electric field multiplied by  $\sqrt{2}$ . The re-plotted spectrum (blue, open squares and curve in Figure 4a) appears to reproduce that obtained for D desorption (black, filled squares and curve in Figure 4a), thus confirming that STM tip-induced H desorption on TiO<sub>2</sub>(110) is indeed due to the proposed tunneling reaction which results from the narrowing of the barrier width by the electric field together with excitation by the tunneling electron (Figure 4b).

Previously, Acharya *et al.* reported a vibrational excitation mechanism for H desorption on TiO<sub>2</sub>(110) based on their STM-AS measurements.<sup>40</sup> They observed (A) no threshold energy, (B) no isotope effects on the reaction yield, (C) no tip position dependence of the reaction yield and (D) a reaction order  $\approx 1.7$ , which we did not observe in our experiments. (A) might be caused by different energy resolutions between the different experiments (current detection circuit, vibration and scanner noise etc.) whereas (B)-(D) are probably caused by different tip positions in our experiments. The STM-AS experiments in ref. 40 were measured with  $V_s = +1.7$  V and  $I_t = 0.5 - 5$  nA. In our experiments, the tunneling reaction was observed with  $V_s = +1.0$  V and  $I_t = 0.001 - 0.5$  nA (TD = +0.1 - -0.1 nm). Thus in the earlier work<sup>40</sup>, a much closer tip-sample distance was used and in that regime, H desorption is caused by vibrational state excitation leading to observations (B)-(D) in ref. 40. We note that when we displace the tip towards the sample by more than -0.1 nm (TD = -0.1 - -0.2 nm, Figure 2), we also did not observe any further shift of STM-AS.

The saturation of the shift as the tip approaches closer to the surface and the origin of the two threshold energies in STM-AS (Figure 2) are not completely understood so far. The

former is probably related to the formation of a chemical bond of the tip with H on TiO<sub>2</sub>(110) and the latter probably related to the electric field that narrows the width of the desorption barrier (see supporting information 7).

## Conclusion

We have investigated the reaction mechanism of the desorption of a single hydrogen on the surface of TiO<sub>2</sub>(110) by STM-AS and DFT calculation under an electronic field. Our results clearly shows the new reaction mechanism of defect control on TiO<sub>2</sub>(110) by a narrowing of the desorption barrier due to the electric field, together with electron excitation. Understanding the role of the tunneling reactions of H may be important for the application of TiO<sub>2</sub> and related materials in electronic devices.<sup>1-8, 41-43</sup>

## Methods

The experiments were performed with a low temperature STM (Omicron GmbH) housed in an ultrahigh vacuum chamber (base pressure:  $4 \times 10^{-9}$  Pa). The TiO<sub>2</sub>(110) samples (Shinkosha, Co. Ltd.) were cleaned by cycles of Ar<sup>+</sup> sputtering (1 keV, 10  $\mu$ A for 10 min) and annealing (900 K for 10 min). The density of O<sub>vac</sub> on pristine TiO<sub>2</sub>(110) was 9%. After cleaning, a small amount ( $1 \times 10^{-8}$  Pa for 3 sec) of H<sub>2</sub>O (or D<sub>2</sub>O) was dosed in the chamber to form H (or D) on the surface. All STM results were obtained at 78 K with electrochemically etched tungsten tips.

To analyze the reaction mechanism, we used DFT calculations of the charged surface under an electric field. The DFT calculations were performed using the Tokyo ab-initio program package (TAPP).<sup>44</sup> We employed the Perdew-Burke-Ernzefhof (PBE) functional as the exchange correlation term<sup>45</sup>, ultrasoft pseudopotentials<sup>46</sup> and a plane wave basis set. In

order to examine the effect of an electric field, the field-induced charge-sheets method was implemented in the DFT calculations.<sup>47</sup> In this method, electrons are subtracted from the slab to realize the positively-charged surfaces, and negatively-charged counter sheets are inserted in the vacuum regions to maintain overall charge neutrality. The TiO<sub>2</sub>(110) surface is modeled by a repeated (1×2) slab made of five TiO<sub>2</sub> trilayers. Single H adsorbs on the surface O site of the slab.

## **ACKNOWLEDGMENT**

This work was supported by Grant No. 21750002 from Ministry of Education, Culture, Sports, Science and Technology of Japan, the Sasakawa Scientific Research Grant from The Japan Science Society, Kurata Grants of Hitachi foundation, Grant for Exploratory Research for Young Scientists of Tohoku University. C.L.P.'s visit to RIKEN was supported by a JSPS BRIDGE Fellowship. T. M. and C. L. P. performed STM experiments with support by N. A., Y. Y., M. K. and Y. K. S. K. and T. N. performed theoretical calculations. T. M., C. L. P. and S. K. wrote the manuscript.

## **Supporting Information Available**

Experimental details and theoretical methods, electronic structure of H/TiO<sub>2</sub>(110), reaction order of H desorption on TiO<sub>2</sub>(110), reduction of the barrier width for H desorption on TiO<sub>2</sub>(110), effects of the STM tip on the desorption of H from TiO<sub>2</sub>(110), tunneling probability of H desorption and saturation of the energy shift and the origin of the threshold energies in the STM-AS measurements; these are available free of charge via the Internet at <http://pubs.acs.org>.

## REFERENCES and NOTES

- (1) Henrich, V. E. *The Surface Science of Metal Oxide*; Cambridge University Press: Cambridge **1994**.
- (2) Diebold, U.; The Surface Science of Titanium Dioxide. *Surf. Sci. Rep.* **2003**, *48*, 53-229.
- (3) Thompson, T.; Yates Jr., J. T.; Surface Science Studies of the Photoactivation of TiO<sub>2</sub>-New Photochemical Processes. *Chem. Rev.* **2006**, *106*, 4428-4453.
- (4) Pang, C. L.; Lindsay, R.; Thornton, G.; Structure of Clean and Adsorbate-Covered Single-Crystal Rutile TiO<sub>2</sub> surfaces. *Chem. Rev.* **2013**, *113*, 3887-3948.
- (5) Dohnálek, Z.; Lyubinetsky, I.; Rousseau, R.; Thermally-Driven Processes on Rutile TiO<sub>2</sub>(110)-(1 x 1): A Direct View at the Atomic Scale. *Prog. Surf. Sci.* **2010**, *85*, 161-205.
- (6) Petek, H.; Zhao, J.; Ultrafast Interfacial Proton-Coupled Electron Transfer. *Chem. Rev.* **2010**, *110*, 7082-7099.
- (7) Henderson, M. A.; A Surface Science Perspective on TiO<sub>2</sub> Photocatalysis. *Surf. Sci. Rep.* **2011**, *66*, 185-297.
- (8) Minato, T.; Atomic Defects in Titanium Dioxide. *Chem. Rec.*, **2014**, *14*, 923-934.
- (9) Minato, T.; Susaki, T.; Shiraki, S.; Kato, H. S.; Kawai, M.; Aika, K.-i.; Investigation of the electronic interaction between TiO<sub>2</sub>(110) surfaces and Au clusters by PES and STM. *Surf. Sci.* **2004**, *566-568*, 1012-1017.
- (10) Minato, T.; Izumi, Y.; Aika, K.-i.; Ishiguro, A.; Nakajima, T.; Wakatsuki, Y.; Nitric Oxide Reduction by Carbon Monoxide over Supported Hexaruthenium Cluster Catalysts. 1. The Active Site Structure That Depends on Supporting Metal Oxide and Catalytic Reaction Conditions. *J. Phys. Chem. B* **2003**, *107*, 9022-9028.
- (11) Henrich, V. E.; Dresselhaus, G.; Zeiger, H. J.; Observation of 2-Dimensional Phases Associated with Defect States on Surface of TiO<sub>2</sub>. *Phys. Rev. Lett.* **1976**, *36*, 1335-1339.
- (12) Knotek, M. L.; Feibelman, P. J.; Ion Desorption by Core-Hole Auger Decay. *Phys. Rev.*

*Lett.* **1978**, *40*, 964-967.

(13) Zhang, Z.; Cao, K.; Yates, Jr., J. T.; Defect-Electron Spreading on the TiO<sub>2</sub>(110) Semiconductor Surface by Water Adsorption. *J. Phys. Chem. Lett.* **2013**, *4*, 674-679.

(14) Suzuki, S.; Fukui, K.; Onishi, H.; Iwasawa, Y.; Hydrogen Adatoms on TiO<sub>2</sub>(110)-(1 x 1) Characterized by Scanning Tunneling Microscopy and Electron Stimulated Desorption. *Phys. Rev. Lett.* **2000**, *84*, 2156-2159.

(15) Minato, T.; Kawai, M.; Kim, Y.; Creation of Single Oxygen Vacancy on Titanium Dioxide Surface. *J. Mat. Res.* **2011**, *27*, 2237-2240.

(16) Lastapis, M.; Martin, M.; Riedel, D.; Hellner, L.; Comtet, G.; Dujardin, G.; Picometer-Scale Electronic Control of Molecular Dynamics inside a Single Molecule. *Science* **2005**, *308*, 1000-1003.

(17) Stipe, B. C.; Rezaei, M. A.; Ho, W.; Inducing and Viewing the Rotational Motion of a Single Molecule. *Science* **1998**, *279*, 1907-1909.

(18) Shen, T. C.; Wang, C.; Abeln, G. C.; Tucker, J. R.; Lyding, J. W.; Avouris, P.; Walkup, R. E.; Atomic-Scale Desorption through Electronic and Vibrational-Excitation Mechanisms. *Science* **1995**, *268*, 1590-1592.

(19) Komeda, T.; Kim, Y.; Kawai, M.; Persson, B. N. J.; Ueba, H.; Lateral Hopping of Molecules induced by Excitation of Internal Vibration Mode. *Science* **2002**, *295*, 2055-2058.

(20) Eigler, D. M.; Lutz, C. P.; Rudge, W. E.; An Atomic Switch Realized with the Scanning Tunneling Microscope. *Nature* **1991**, *352*, 600-603.

(21) Gimzewski, J. K.; Joachim, C.; Nanoscale Science of Single Molecules using Local Probes. *Science* **1999**, *283*, 1683-1688.

(22) Carpinelli, J. M.; Swartzentruber, B. S.; Direct Measurement of Field Effects on Surface Diffusion. *Phys. Rev. B.* **1998**, *58*, R13423-13425.

(23) Mo, Y. W.; Reversible Rotation of Antimony Dimers on the Silicon (001) Surface with a

Scanning Tunneling Microscope. *Science* **1993**, *261*, 886-888.

(24) Alemani, M.; Peters, M. V.; Hecht, S.; Rieder, K.-H.; Moresco, F.; Grill, L.; Electric Field-induced Isomerization of Azobenzene by STM. *J. Am. Chem. Soc.* **2006**, *128*, 14446-14447.

(25) Stroschio, J. A.; Celotta, R. J.; Controlling the Dynamics of a Single Atom in Lateral Atom Manipulation. *Science*, **2004**, *306*, 242-247.

(26) Kumagai, T.; Kaizu, M.; Hatta, S.; Okuyama, H.; Aruga, T.; Direct Observation of Hydrogen-Bond Exchange within a Single Water Dimer. *Phys. Rev. Lett.* **2008**, *100*, 166101.

(27) Wendt, S.; Schaub, R.; Matthiesen, J.; Vestergaard, E. K.; Wahlstrom, E.; Rasmussen, M. D.; Thostrup, P.; Molina, L. M.; Laegsgaard, E.; Stensgaard, I.; Hammer, B.; Besenbacher, F.; Oxygen Vacancies on TiO<sub>2</sub>(110) and their Interaction with H<sub>2</sub>O and O<sub>2</sub>: A Combined High-Resolution STM and DFT Study. *Surf. Sci.* **2005**, *598*, 226-245.

(28) Lackinger, M.; Janson, M. S.; Ho, W.; Localized Interaction of Single Porphyrin Molecules with Oxygen Vacancies on TiO<sub>2</sub>(110). *J. Chem. Phys.* **2012**, *137*, 234707.

(29) Minato, T.; Asao, N.; Yamamoto, Y.; Kawai, M.; Kim, Y.; Photoresponse on the Desorption of an Atomic Hydrogen on Titanium Dioxide Surface Induced by a Tip of Scanning Tunneling Microscope *Chem. Lett.* **2013**, *42*, 942-943.

(30) An additional threshold at lower energy could not be observed because of the low tunneling current.

(31) Henderson, M. A.; An HREELS and TPD study of water on TiO<sub>2</sub>(110): The Extent of Molecular *versus* Dissociative Adsorption. *Surf. Sci.* **1996**, *355*, 151-166.

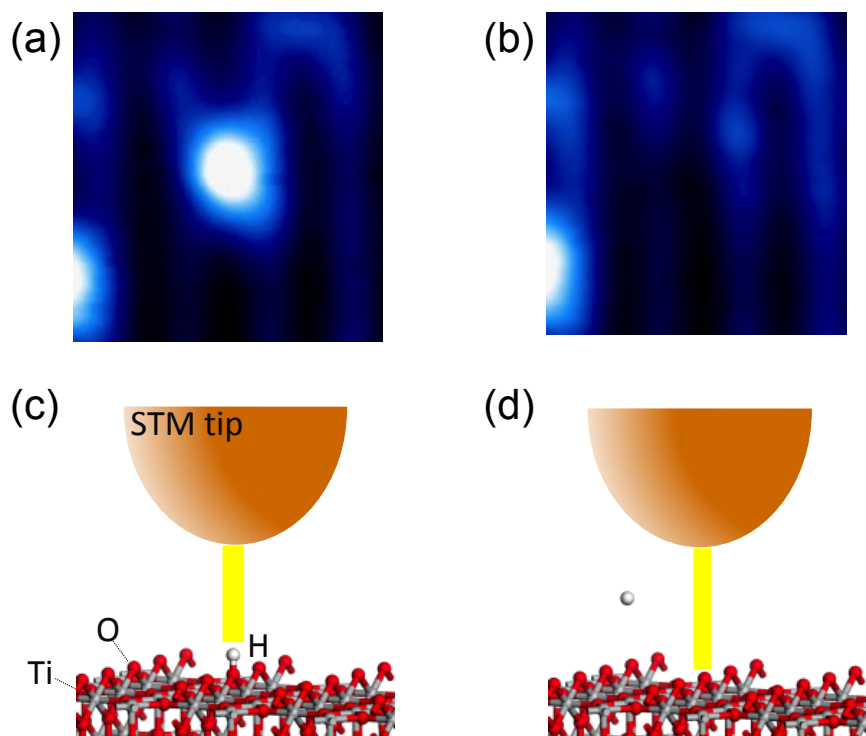
(32) DFT calculations using the GGA functional underestimate the energy barrier<sup>33-34</sup>. The true energy barrier should be higher than 3.5 eV.

(33) Lindan P. J. D.; Zhang, C.; Exothermic Water Dissociation on the rutile TiO<sub>2</sub>(110) Surface. *Phys. Rev. B* **2005**, *72*, 075439.

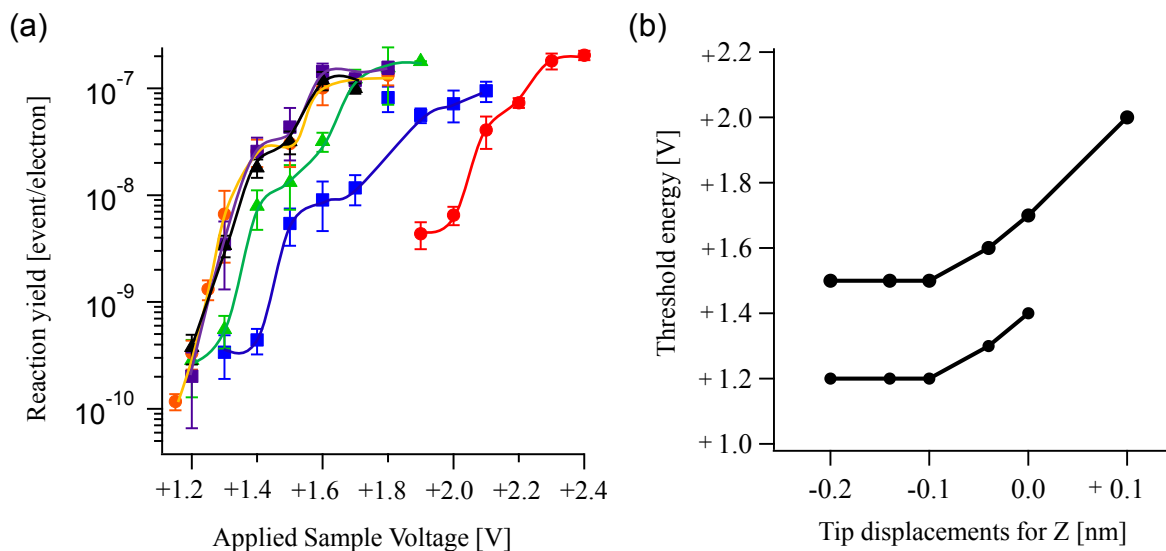
- (34) Jursic, B. S.; Density Functional Theory Study of Radical Hydrogen Abstraction with Hydrogen and Hydroxyl Radicals. *Chem. Phys. Lett.* **1996**, *256*, 603-608.
- (35) Minato, T.; Sainoo, Y.; Kim, Y.; Kato, H. S.; Aika, K.-i.; Kawai, M.; Zhao, J.; Petek, H.; Huang, T.; He, W.; Wang, B.; Wang, Z.; Zhao, Y.; Yang, J.; Hou, J. G.; The Electronic Structure of Oxygen Atom Vacancy and Hydroxyl Impurity Defects on Titanium Dioxide (110) Surface. *J. Chem. Phys.* **2009**, *130*, 124502.
- (36) Feenstra, R. M.; Electrostatic Potential for a Hyperbolic Probe Tip near a Semiconductor. *J. Vac. Sci. Technol. B*, **2003**, *21*, 2080-2088.
- (37) Kajita, S.; Minato, T.; Kato, H. S.; Kawai, M.; Nakayama, T.; First-Principles Calculations of Hydrogen Diffusion on Rutile TiO<sub>2</sub>(110) Surfaces. *J. Chem. Phys.* **2007**, *127*, 104709.
- (38) Zhao, J.; Li, B.; Jordan, K. D.; Yang, J.; Petek H.; Interplay Between Hydrogen Bonding and Electron Solvation on Hydrated TiO<sub>2</sub>(110). *Phys. Rev. B* **2006**, *73*, 195309 1-10.
- (39) Bohm, D.; Quantum Theory, Dover New York, (1989).
- (40) Acharya, D. P.; Ciobanu, C. V.; Camillone, N.; Sutter, P.; Mechanism of Electron-Induced Hydrogen Desorption from Hydroxylated Rutile TiO<sub>2</sub>(110). *J. Phys. Chem. C* **2010**, *114*, 21510-21515.
- (41) Spahr, E. J.; Wen, L.; Stavola, M.; Boatner, L. A.; Feldman, L. C.; Tolk, N. H.; Lupke, G.; Giant Enhancement of Hydrogen Transport in Rutile TiO<sub>2</sub> at Low Temperatures *Phys. Rev. Lett.* **2010**, *104*, 205901.
- (42) Varghese, O. K.; Gong, D.; Paulose, M.; Ong, K. G.; Grimes, C. A.; Hydrogen Sensing using Titania Nanotubes *Sensors and Actuators B* **2003**, *93*, 338.
- (43) Gopel, W.; Rucker, G.; Feierabend, R.; Intrinsic defects of TiO<sub>2</sub>(110): Interaction with chemisorbed O<sub>2</sub>, H<sub>2</sub>, CO, and CO<sub>2</sub>. *Phys. Rev. B* **1983**, *28*, 3427-3438.



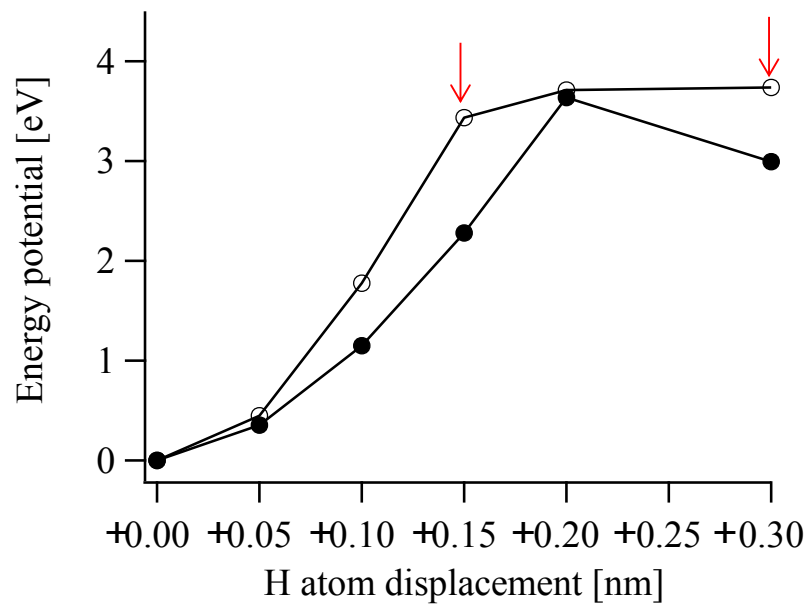
- (44) Yamauchi, J.; Tsukada, M.; Watanabe, S.; Sugino, O.; First-Principles Study on Energetics of c-BN(001) Reconstructed Surfaces. *Phys. Rev. B* **1996**, *54*, 5586-5603.
- (45) Perdew, J. P.; Burke, K.; Ernzerhof, M.; Generalized Gradient Approximation made Simple. *Phys. Rev. Lett.* **1996**, *77*, 3865-3868.
- (46) Vanderbilt, D. Soft Self-Consistent Pseudopotentials in a Generalized Eigenvalue Formalism. *Phys. Rev. B* **1990**, *41*, 7892-7895.
- (47) Kajita, S.; Nakayama, T.; Kawai, M.; Ab-initio Calculation Method for Electronic Structures of Charged Surfaces using Repeated Slab and Density-Variable Charge Sheets. *J. Phys. Soc. Jpn.* **2007**, *76*, 044701.



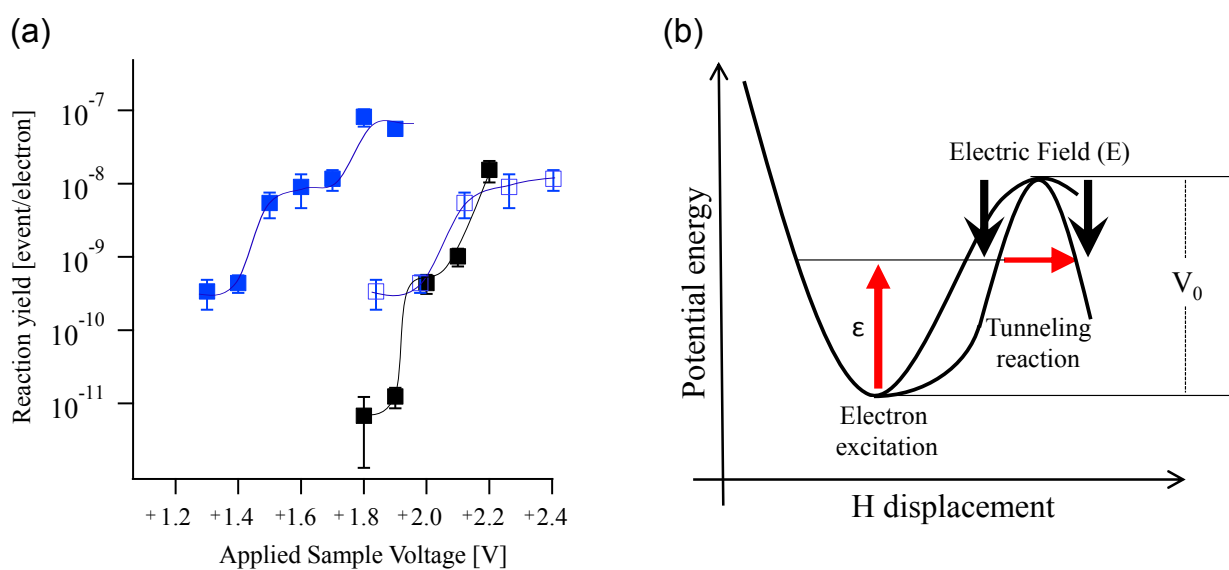
**Figure. 1.** STM images of  $\text{TiO}_2(110)$  (a) before and (b) after H desorption ( $2.7 \text{ nm} \times 3.0 \text{ nm}$ ,  $V_s = +1.5 \text{ V}$ ,  $I_t = 0.3 \text{ nA}$ ). (c) and (d) are schematic images of H desorption on  $\text{TiO}_2(110)$ .



**Figure 2.** (a) STM-AS of H desorption on  $\text{TiO}_2(110)$ . The spectrum with blue, filled squares is obtained with start parameters,  $V_s = +1.0$  V,  $I_t = 0.02$  nA, and with no tip displacement (i.e.  $\text{TD} = 0$  nm). All other spectra have the same start parameters but with different TD. Red, filled circles:  $\text{TD} = +0.1$  nm; green, filled triangles:  $\text{TD} = -0.04$  nm; orange, filled circles:  $\text{TD} = -0.10$  nm; purple, filled squares:  $\text{TD} = -0.14$  nm, black, filled triangles:  $\text{TD} = -0.20$  nm. (b) Threshold energy observed in STM-AS depending on TD.



**Figure. 3.** Potential energy of H as a function of the displacement from the surface of  $\text{TiO}_2(110)$  under an electric field as calculated using DFT. Open circles: 0.0 V/nm; filled circles: 4.5 V/nm.



**Figure 4.** (a) STM-AS measurements of the desorption of atomic H (blue filled squares) and atomic D (black filled squares) from  $\text{TiO}_2(110)$ . The STM-AS results for H are also re-plotted with the applied electric field multiplied by  $\sqrt{2}$  (blue open squares). The initial tip position was  $V_s = +1.0$  V,  $I_t = 0.02$  nA. (b) Schematic energy diagram for H desorption on  $\text{TiO}_2(110)$ .

Insert Table of Contents Graphic and Synopsis Here

