

An Electric Field–Induced Change in the Selectivity of a Metal Oxide–Catalyzed Epoxide Rearrangement

Craig F. Gorin, Eugene S. Beh, and Matthew W. Kanan*

Stanford University, Department of Chemistry, 337 Campus Drive, Stanford, California 94305, United States

S Supporting Information

ABSTRACT: The rearrangement of *cis*-stilbene oxide catalyzed by Al₂O₃ was studied in the presence of interfacial electric fields. Thin films of Al₂O₃ deposited on Si electrodes were used as the opposing walls of a reaction vessel. Application of a voltage across the electrodes engendered electrochemical double layer formation at the Al₂O₃–solution interface. The aldehyde to ketone product ratio of the rearrangement was increased by up to a factor of 63 as the magnitude of the double layer charge density was increased. The results support a field–dipole effect on the selectivity of the catalytic reaction.

Controlling selectivity is arguably the principal challenge facing the development of efficient chemical syntheses.^{1,2} For an irreversible reaction, selectivity is determined by the relative magnitudes of competing activation barriers on the reaction’s potential energy surface. Because this surface is determined by the chemical structures of the reaction components, efforts to control selectivity have necessitated making changes to one or more of these components. Identifying structural features that induce selectivity can be extremely challenging because of the complexities of molecular structure–activity relationships. In principle, however, an externally applied electric field could also be used to control selectivity through field–dipole interactions. This concept is particularly appealing because all unique molecules and transition states have unique interactions with an electric field determined by their structure-specific charge distributions.

Previous experimental studies have demonstrated that static electric fields affect the rates of electron transfer reactions in enzymatic and synthetic systems,^{3–5} and a recent study has provided spectroscopic evidence for an interfacial electric field effect on the tautomerization equilibrium of an electrode-attached synthetic molecule.⁶ Large electric fields (1–10 V/nm) within zeolite cavities have been exploited for visible-light photooxidations of simple hydrocarbons with O₂.^{7,8} Naturally occurring electric fields in enzyme active sites have also been implicated as major contributors to enzymatic catalysis.^{9,10} Furthermore, density functional theory studies of reactions in uniform electric fields have concluded that selectivity is highly sensitive to strong fields.^{11–13} To date, however, a general method to apply large electric fields to reactions and study their effects on selectivity has not been developed.

Researchers have previously demonstrated that electrochemical changes of conductive catalysts can alter the rates of

nonelectrochemical reactions including gas phase oxidations of simple hydrocarbons with O₂, oxidation of H₂ with O₂, and alkene isomerizations.^{14–18} This electrochemical promotion of catalysis (EPOC) results from voltage-induced ion migration onto the conductive catalyst surface that changes the work function or available active sites.^{15,19,20} In contrast, we hypothesized that the local electric field of a catalytic reaction could be controlled without effecting electrochemical changes to the catalyst by localizing it to a suitably designed electrode–electrolyte interface. Here we demonstrate that externally controlled double layer charge density changes the selectivity of epoxide rearrangement reactions catalyzed by an insulating Lewis acidic metal oxide. Our results are consistent with a field–dipole origin of the selectivity changes and provide a general experimental method to evaluate electric field effects on catalytic reactions.

To study electric field effects on catalytically active metal oxides, we designed a reaction vessel (the “parallel plate cell”) that enables the electrostatic environment of a solution-exposed metal oxide to be controlled with a voltage source (Figures 1 and S3). The parallel plate cell employs two heavily p-doped Si electrodes. Each electrode is coated on one side with a thin (45 Å) layer of Al₂O₃ that is deposited by using atomic layer deposition (ALD) (see Supporting Information).²¹ The Al₂O₃ layer of one of the electrodes is used as the catalytically active oxide in the parallel plate cell experiments (the “catalyst electrode”); the Al₂O₃ layer of the other electrode is coated with an alkylphosphonic acid monolayer to block reactivity at this surface (the “counter electrode”). In an assembled parallel plate cell, the two electrodes are separated by a 500 μm thick perfluorinated gasket with a rectangular opening in the center; an electrolyte solution containing the substrate for a reaction occupies the volume between the two electrodes determined by the dimensions of the gasket. Application of a voltage between the two electrodes generates electrochemical double layers at each interface and places the exposed Al₂O₃ layer on the catalyst electrode in an interfacial electric field.

The strength of the interfacial electric field at the surface of the exposed Al₂O₃ layer depends on the extent of double layer charging, i.e. the charge density on the Si electrode that is balanced by electrolyte ions at the oxide–electrolyte interface. To measure this charge density as a function of the applied voltage (*V*), we performed double step chronocoulometry²² with fully assembled cells. The cells were comprised of 45 Å of Al₂O₃ on the catalyst electrode and 45 Å of Al₂O₃ coated with a

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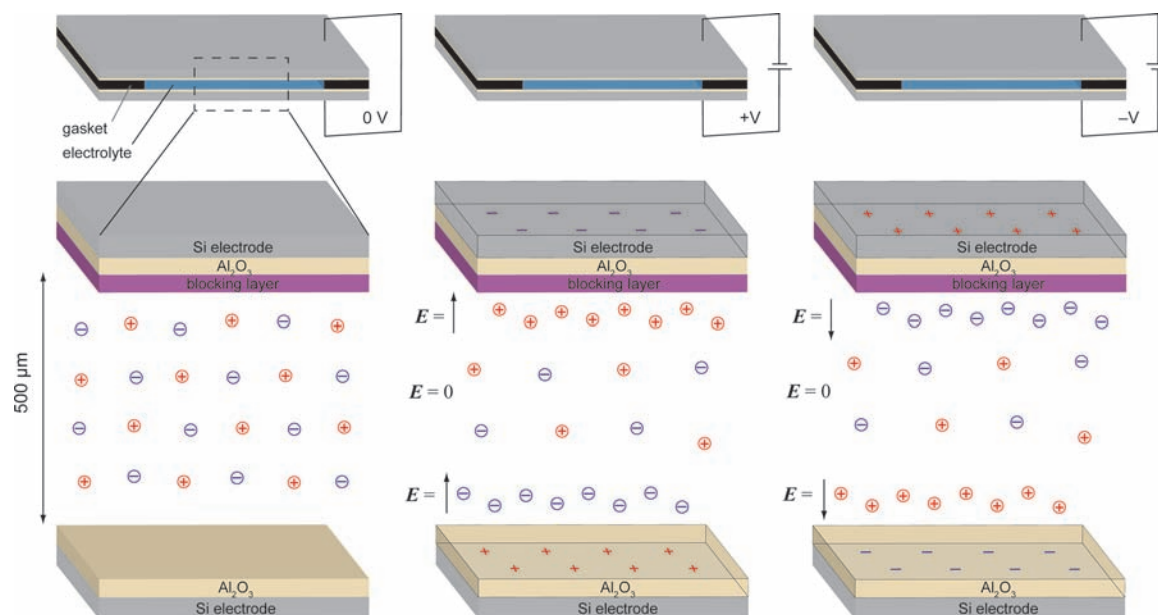


Figure 1. Parallel plate cell. Cross-sectional illustration of the cell (top) and expanded illustration of the metal oxide–electrolyte interfaces (bottom) at 0 V (left), positive voltage (middle), and negative voltage (right). Significant V -dependent electric fields are present only at the interfaces. The top Al_2O_3 layer is blocked with an alkylphosphonic acid monolayer to confine catalysis to the bottom Al_2O_3 layer.

monolayer of octylphosphonic acid²³ on the counter electrode. In a CH_3CN or CH_2Cl_2 solution containing 0.5 mM tetrabutylammonium hexafluorophosphate (TBAPF_6), the charge vs time curves exhibit a rapid (< 50 ms) rise that is characteristic of double layer charging. A similar discharge is observed upon stepping back to 0 V (Figure S4). The amount of double layer charging increases approximately linearly with V (Figure 2). For $|V| > 2$ V, double layer charging in excess of $1 \mu\text{C}/\text{cm}^2$ is observed. These values are comparable to double layer charge densities measured for metal electrodes in contact with dilute electrolytes in CH_3CN .²⁴ The difference in charge densities measured in CH_2Cl_2 and CH_3CN likely reflects the difference in polarity of these solvents. The chronocoulometric measurements are also consistent with the double layer capacitance values obtained from electrochemical impedance spectroscopy measurements (Table S1).

The charge densities measured by chronocoulometry indicate that voltage-dependent field strengths on the order

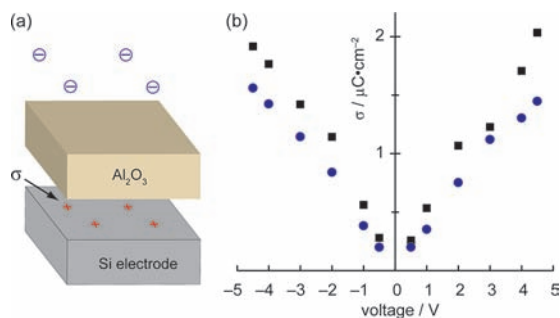


Figure 2. (a) Schematic expanded view of the Al_2O_3 –electrolyte interface at positive V . Charge density on the underlying Si (σ) is balanced by electrolyte ions. (b) Chronocoulometric measurement of σ at selected voltages in the parallel plate cell with 0.5 mM TBAPF_6 in CH_3CN (black squares) and CH_2Cl_2 (blue circles). Data are shown for a cell with 45 Å of Al_2O_3 on each electrode and an octylphosphonic acid monolayer on the counter electrode.

of 1 V/nm are present at $|V| > 3$ V in the parallel plate cell.²⁵ Indirect measurements of field strengths at other electrode–electrolyte interfaces have yielded similar values.^{5,6,26} Field strengths of this magnitude are sufficient to significantly affect the selectivity of a reaction. For example, if two competing transition states arise from a common intermediate, the field effect on selectivity is determined solely by the difference between its effects on the transition states. If the charge distributions of the transition states in the presence of the electric field E are approximated as dipole moments μ_1 and μ_2 , the energetic differentiation induced by E is given by $\Delta U = E \cdot \Delta\mu$, where $\Delta\mu = \mu_1 - \mu_2$. According to this model, a 1 V/nm electric field would induce an ~ 10 -fold change in selectivity at 300 K if the projection of $\Delta\mu$ along the field axis were 2.8 D ($E \cdot \Delta\mu = 1.4$ kcal/mol).

Lewis acidic metal oxides including Al_2O_3 are known to catalyze numerous organic reactions including epoxide rearrangements.^{27,28} To study electric field effects on Al_2O_3 catalysis, we selected the rearrangement of *cis*-stilbene oxide (**1**) to diphenylacetaldehyde (**2**) and diphenylethanone (**3**) as a model reaction (Figure 3a). Parallel plate cell reactions were performed in cells with 45 Å of Al_2O_3 on the catalyst electrode and 45 Å of Al_2O_3 coated with an octylphosphonic acid layer on the counter electrode. The electrolyte solution consisted of 5 mM **1** and 0.5 mM TBAPF_6 in either CH_3CN or CH_2Cl_2 . After assembly of the cell, either the electrodes were connected by a short circuit (0 V) or a constant voltage was applied across the two electrodes by using a sourcemeter. Parallel plate cell reactions were allowed to proceed for 16 h. At the conclusion of each experiment, the cell was disassembled and the conversion and product ratio were determined by using high-pressure liquid chromatography (HPLC). For $V \leq 5$ V, a leakage current of 2–10 nA/cm² is observed over the course of the experiment (Figures S6 and S7), corresponding to a total moles of charge passed that is ~ 0.5 –2.5% of the total moles of **1** in the cell. Voltages > 5 V lead to a dielectric breakdown and increasing currents over time.

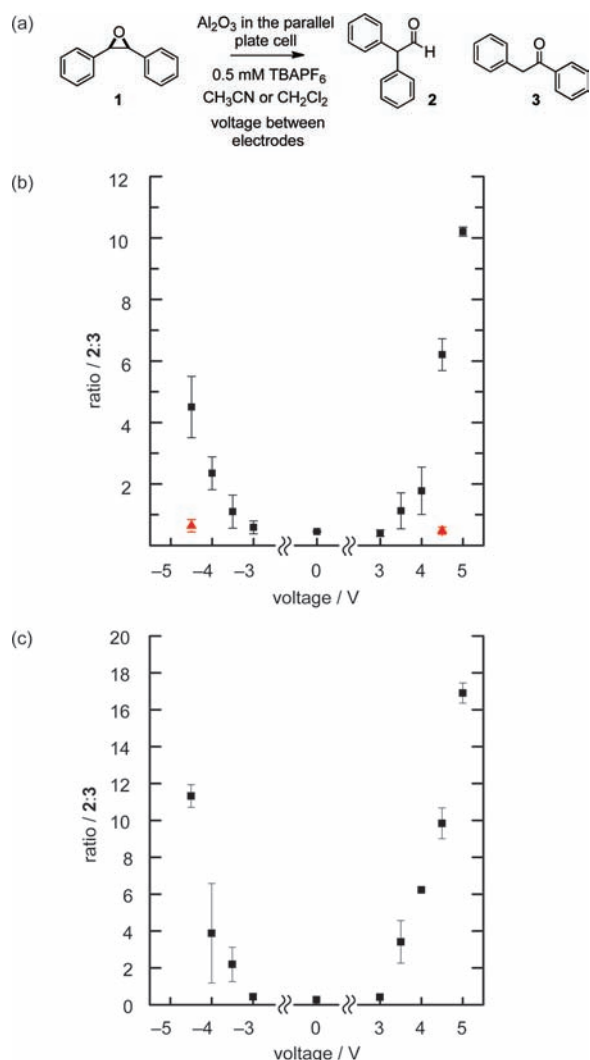


Figure 3. (a) Reaction scheme for the rearrangement of *cis*-stilbene oxide in the parallel plate cell. Product ratios as a function of voltage are shown for experiments in CH₃CN (b) and CH₂Cl₂ (c). Black squares correspond to experiments with octylphosphonic acid on the counter electrode. Red triangles correspond to experiments with octadecylphosphonic acid on the counter electrode.

The product ratio for the rearrangement of **1** catalyzed by an Al₂O₃ layer in the parallel plate cell exhibits strong dependence on V (Figure 3b). In all cases, the reaction proceeds cleanly such that the products **2** and **3** and remaining starting material **1** account for nearly all of the material detected by HPLC. At 0 V in CH₃CN, 5% of **1** is converted to **2** and **3** in a 1:2.2 ratio, similar to the ratio that is observed for the reaction catalyzed by Al₂O₃ powder in the same solution (see Supporting Information for V -dependent conversion data and for experiments with Al₂O₃ powders). For $|V| \leq 3$ V, negligible changes in the selectivity are observed. However, for $V > 3$ V, the 2:3 ratio increases exponentially as V is increased and the conversions are 2–4-fold higher than at 0 V. At +5 V, the 2:3 ratio is 10.2:1, representing an ~22-fold enhancement over the ratio at 0 V. Strikingly, a similar trend is observed at negative voltages. For $V < -3$ V, the 2:3 ratio increases exponentially as the voltage is decreased and the conversions are 2–5-fold higher than at 0 V; at –4.5 V the ratio is 4.5:1, representing an ~10-fold enhancement over the 0 V ratio. At voltages where dielectric breakdown is observed, large

quantities of additional unidentified products are observed by HPLC.

The electric field strength at the surface of the exposed Al₂O₃ layer in the parallel plate cell can also be adjusted by changing the double layer capacitance of the cell. Accordingly, an electric field effect on selectivity should depend on capacitance in addition to V . To test this hypothesis, we prepared a cell in which the counter electrode was coated with an octadecylphosphonic acid layer instead of an octylphosphonic acid layer. The extended hydrocarbon chain was expected to lower the capacitance of the counter electrode interface. In 0.5 mM TBAPF₆ in CH₃CN, the double layer charge densities determined by chronocoulometry for this cell at +4.5 and –4.5 V are 1.56 and 1.52 $\mu\text{C}/\text{cm}^2$, respectively, ~0.5 $\mu\text{C}/\text{cm}^2$ lower than the corresponding values for a cell with an octylphosphonic acid coated counter electrode. At 0 V, the 2:3 ratio is the same for experiments in cells with the two different counter electrodes; however, at ± 4.5 V, the 2:3 ratios for a cell with an octadecylphosphonic acid-coated counter electrode are unchanged (Figure 3b, red triangles), in sharp contrast to the ~10-fold increases observed for cells with an octylphosphonic acid layer on the counter electrode. These results indicate that selectivity changes in the parallel plate cell depend not on V by itself, but on double layer charge densities, as required for a field–dipole effect. In this case, the double layer charge density at the exposed Al₂O₃ layer and its effect on selectivity were lowered by changing the blocking layer on the counter electrode 500 μm away.

Larger V -dependent selectivity changes are observed for parallel plate cell reactions performed in 0.5 mM TBAPF₆ in CH₂Cl₂ with octylphosphonic acid on the counter electrode than in CH₃CN (Figure 3c). At 0 V, the reaction proceeds in 4% conversion to form a 1:3.7 ratio of 2:3. For $|V| > 3$ V, the conversions are > 10-fold higher and the 2:3 ratios increase exponentially with voltage to reach 16.9:1 at +5 V and 11.3:1 at –4.5 V, representing ~63- and ~42-fold enhancements, respectively. The larger selectivity changes in CH₂Cl₂ may reflect a more compact electrochemical double layer,²² which engenders larger fields at the Al₂O₃ surface. This effect could outweigh the somewhat smaller double layer charge density in CH₂Cl₂ compared to CH₃CN, as measured by chronocoulometry (see Figure 2b).

In control experiments, very low (< 1%) conversions of **1** are observed for reactions in parallel plate cells with octylphosphonic acid monolayers on both Al₂O₃ layers at 0 V or ± 4.5 V, indicating that the reaction takes place at the Al₂O₃ surface, as expected. To determine whether voltage permanently alters the Al₂O₃ layers, catalyst electrodes that had previously been used at +4.5 V in a parallel plate cell reaction were subsequently reused in a parallel plate cell at 0 V with a fresh solution of **1**. The conversion and selectivity with the reused electrode at 0 V matched that of a fresh catalyst electrode at 0 V, indicating that an applied voltage does not lead to an irreversible change in the Al₂O₃ layer that alters its catalytic activity. Additional control experiments ruled out the contribution of electrolytically generated H⁺ to the observed selectivity changes (see Supporting Information).

Together, the chronocoulometry, voltage-dependent selectivity data and associated control experiments are consistent with an electric field effect on the rearrangement of *cis*-stilbene oxide catalyzed by Al₂O₃. The double layer charge density increases approximately linearly with V , generating V -dependent interfacial electric fields. While the strength of the field at

the molecular level cannot be determined by the measurements described here, field strengths on the order of 1 V/nm are reasonable given the measured charge densities. Significantly higher transient electric fields may also be accessible in the vicinity of the electrolyte ions that accumulate at the interface. The largest selectivity change observed here, a factor of 63, corresponds to a 2.5 kcal/mol perturbation of the difference between activation barriers leading to the two products. To account for this perturbation with a field dipole model in which the field is 1 V/nm, the difference in dipole moments between the competing activation barriers ($\Delta\mu$) must be 5.1 D along the direction of the field. We hypothesize that the transition state leading irreversibly to **2** has a dipole moment that is several debye larger than the transition state leading to **3** and that the reactants/transition states are readily aligned in the local field at the interface. Thus, field–dipole interactions lower the barrier to **2** relative to **3** to an extent that depends on the magnitude of the local field but not its direction, accounting for the symmetry of the selectivity changes at $\pm V$. Interactions between the local field and induced dipole moments as well as ordering of the solvent molecules at the interface due to field–solvent dipole interactions may also contribute to the selectivity changes.

The results obtained for the reaction of **1** catalyzed by Al_2O_3 in the parallel plate cell are not unique to this combination of substrate and catalyst. In a preliminary examination of an alternative substrate, a 30–40-fold change in the ratio of aldehyde to ketone products is observed at ± 4.5 V relative to 0 V if 2-(4-chlorophenyl)-3-phenyloxirane is used as the substrate. In addition, a 2–7-fold change in the ratio of **2**:**3** is observed at ± 4.5 V relative to 0 V if an HfO_2 layer is used as the catalyst instead of Al_2O_3 (see Supporting Information).

The breakdown voltage and interfacial capacitance of the Al_2O_3 -coated Si electrodes limit the maximum attainable interfacial field strength in the parallel plate cell. The use of alternative insulating layers²⁹ with higher dielectric constants or alternative electrolytes such as ionic liquids^{30,31} may enable the application of substantially larger fields. For reactions in which $E \cdot \Delta\mu$ contributes to $\Delta\Delta G^\ddagger$, such increases would dramatically improve the control over selectivity afforded by this approach.

Localizing other thin film, nanoparticle, or molecular catalysts in interfacial fields will enable the study of field effects across a wide spectrum of reactions. Furthermore, the design principles of the parallel plate cell may in theory be extended to flow reactors that enable field effects to be exploited on a preparative scale. We anticipate that field effects will provide a general approach toward controlling the selectivity of catalytic reactions.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures, characterization data for the oxide-coated wafers, and additional control experiments. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author
mkanan@stanford.edu

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