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### Title

Direct observation of surface ethyl to ethane interconversion upon C<sub>2</sub>H<sub>4</sub> hydrogenation over Pt/Al<sub>2</sub>O<sub>3</sub> catalyst by time-resolved FT-IR spectroscopy

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**Direct Observation of Surface Ethyl to Ethane Interconversion upon C<sub>2</sub>H<sub>4</sub>  
Hydrogenation over Pt/Al<sub>2</sub>O<sub>3</sub> Catalyst by Time-Resolved FT-IR Spectroscopy**

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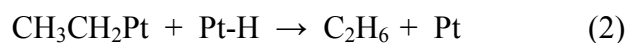
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## Abstract

Time-resolved FT-IR spectra of ethylene hydrogenation over alumina-supported Pt catalyst were recorded at 25 ms resolution in the temperature range 323 to 473 K using various H<sub>2</sub> flow rates (1 atm total gas pressure). Surface ethyl species (2870 and 1200 cm<sup>-1</sup>) were detected at all temperatures along with the gas phase ethane product (2954 and 2893 cm<sup>-1</sup>). The CH<sub>3</sub>CH<sub>2</sub>Pt growth was instantaneous on the time scale of 25 ms under all experimental conditions. At 323 K, the decay time of surface ethyl (122 ± 10 ms) coincides with the rise time of C<sub>2</sub>H<sub>6</sub> (144 ± 14 ms). This establishes direct kinetic evidence for surface ethyl as the kinetically relevant intermediate. Such a direct link between the temporal behavior of an observed intermediate and the final product growth in a heterogeneous catalytic system has not been demonstrated before to our knowledge. A fraction (10 percent) of the asymptotic ethane growth at 323 K is prompt, indicating that there are surface ethyl species that react much faster than the majority of the CH<sub>3</sub>CH<sub>2</sub>Pt intermediates. The dispersive kinetics is attributed to the varying strength of interaction of the ethyl species with the Pt surface caused by heterogeneity of the surface environment. At 473 K, the majority of ethyl intermediates are hydrogenated prior to the recording of the first time slice (24 ms), and a correspondingly large prompt growth of ethane is observed. The yield and kinetics of the surface ethylidyne are in agreement with the known spectator nature of this species.

## 1. Introduction

Efforts to understand the detailed mechanism of heterogeneous catalytic hydrogenation of ethylene over noble metal catalysts continues to be of intense interest despite the large number of studies on this subject by many groups.<sup>1</sup> Hydrogenation of alkenes is of major industrial importance,<sup>2</sup> and the prototype C<sub>2</sub>H<sub>4</sub> system has long served as a main focus for advancing the knowledge of this reaction type. In particular, vibrational spectroscopic studies of the reaction over single crystal Pt surfaces or finely dispersed Pt particles on silica or alumina under steady-state conditions<sup>1</sup> led to the acceptance of stepwise hydrogenation mechanism originally proposed by Horiuti and Polanyi.<sup>3</sup> In this mechanism, surface adsorbed ethylene is hydrogenated to ethyl and subsequently converted to ethane.



Adsorbed ethylene is known to exist in a weakly  $\pi$ -bonded or more strongly di- $\sigma$ -bonded form based on reflection-absorption infrared and HREELS studies on Pt(111) surfaces,<sup>4-8</sup> and transmission IR spectroscopy of supported metal particle catalysts.<sup>9,10</sup> Various experimental studies have provided convincing evidence that the hydrogenation step (1) involves  $\pi$ -C<sub>2</sub>H<sub>4</sub> species.<sup>11-16</sup> Using sum frequency generation spectroscopy (SFG) for monitoring the CH stretching region, Somorjai and coworkers have identified absorption bands of  $\pi$ -bonded ethylene over Pt(111) under high pressure conditions at room temperature and demonstrated that it is the species being hydrogenated.<sup>1b,15</sup> The same

study revealed peaks assigned to surface ethyl species, hydrogenation of which was proposed to constitute the main reaction path.

$\pi$ -C<sub>2</sub>H<sub>4</sub> and ethyl species were also detected by FT-IR in steady state hydrogenation experiments over supported IR clusters.<sup>17</sup> On the other hand, the ethylidyne surface species (CH<sub>3</sub>CPT<sub>3</sub>) familiar from early HREELS and reflection-absorption infrared surface work<sup>8,9,18,19</sup> was determined to play no kinetically significant role in the catalytic hydrogenation.<sup>9,20,21</sup> These experimental findings on Pt or Pd surfaces are supported by recent DFT computational work.<sup>22-25</sup> The papers predict that the barrier to hydrogenation is substantially lower for  $\pi$ -C<sub>2</sub>H<sub>4</sub> than for di- $\sigma$  ethylene (at the high surface coverage relevant for reaction conditions), and that the barrier for ethyl to ethane conversion exceeds that of step (1) by a factor between 2 and 5.

In an attempt to obtain direct evidence for the kinetic relevancy of the ethyl intermediate of C<sub>2</sub>H<sub>4</sub> hydrogenation under reaction conditions, we have monitored the catalysis by time-resolved FT-IR spectroscopy using the rapid-scan method. A preliminary study of the catalysis over alumina-supported Pt catalyst at 473 K under continuous H<sub>2</sub>/N<sub>2</sub> flow (1 atm) and pulsed release of C<sub>2</sub>H<sub>4</sub> (30 ms duration) revealed two transient intermediates, namely ethylidyne (2880 and 1339 cm<sup>-1</sup>) and a species absorbing at 1200 cm<sup>-1</sup>, assigned to surface ethyl.<sup>26</sup> The rise of both intermediates was too fast to be resolved on the 100 ms time scale. As expected, the decay time of the CH<sub>3</sub>CH<sub>2</sub>Pt species (around the time limit of 100 ms) was faster than that of CH<sub>3</sub>CPT<sub>3</sub> (300 ms). Nevertheless, given the vast difference in their mechanistic role (ethylidyne is a mere spectator)<sup>1b</sup>, the lifetimes of the two surface species were surprisingly close. Moreover, the ethane growth was already

close to its maximum in the first recorded time slice, suggesting that the ethyl species exhibits dispersive hydrogenation kinetics with the majority of the intermediates reacting at times shorter than 100 ms when running at 473 K.

In order to establish the kinetic relationship between the decay of the surface ethyl species and the rise of the gas phase ethane, we have conducted a comprehensive FT-IR study of the temperature (323-473 K) and hydrogen concentration dependence of the temporal behavior of the  $C_2H_4 + H_2$  reaction over  $Pt/Al_2O_3$  at 25 ms resolution. Taking advantage of the slower kinetics at the lower temperatures, we show in this paper that the surface ethyl decay coincides with the rate of ethane growth, thus demonstrating directly the kinetic relevancy of the surface ethyl intermediate.

## 2. Experimental Section

Time-resolved FT-IR spectra were recorded in the rapid-scan mode on a Bruker model IFS88 spectrometer equipped with a HgCdTe PV detector Kolmar Technologies model KMPV8-1-J2 (8 micron bandgap) or a HgCdTe PV detector model KMPV11-1-J2 (12 micron bandgap). The mirror velocity was 160 kHz, and the spectral resolution was  $4\text{ cm}^{-1}$ . The protocol for obtaining the transient spectra consisted of the recording of 99 interferograms (double-sided/ forward-backward) following a  $C_2H_4$  pulse, corresponding to 396 single-sided interferograms. Four spectral time slices of 25 ms duration were extracted from the first and four more from the second forward-backward mirror motion

after the ethylene pulse, while the 4 interferograms of each subsequent forward-backward motion were automatically averaged for S/N improvement, furnishing spectral time slices at 128 ms resolution. A total of 50 such sets of single beam spectra generated by 50 ethylene pulses were stored as the result of one experiment. Final time-resolved spectra for a given time delay were obtained by calculating the ratio of each of the 50 corresponding stored single beam spectra against the single beam spectrum taken just before the pulse. The 50 ratioed spectra were then averaged to yield the absorbance time slice for a given time delay. The results of 10 such experiments were averaged for further S/N improvement.

The Al<sub>2</sub>O<sub>3</sub>-supported, finely divided Pt catalyst (Exxon HFR-100, 5% Pt, calcined at 823 K, BET surface area 180 m<sup>2</sup>g<sup>-1</sup>) was prepared in the form of a pressed wafer with an embedded W grid. The catalyst material was provided by Dr. Joel Ager at LBNL. The latter is made of a 0.49 in. diameter tungsten foil (thickness 0.002 in.) featuring laser-drilled 0.012 in. holes. The grid, which was held by a Ni jaw similar to a design described by Yates<sup>27</sup> was electrically heated and the temperature monitored by a thermocouple mounted on the W grid. The catalyst was situated in the center of home built 100 cm<sup>3</sup> stainless steel reactor cell equipped with two flange-mounted BaF<sub>2</sub> windows for transmission infrared spectroscopy. The catalyst was transparent in the region 5000-800 cm<sup>-1</sup> (reduced sensitivity below 1100 cm<sup>-1</sup> because of Al-O stretch absorption). The continuous flow of a H<sub>2</sub>/N<sub>2</sub> mixture (4.5 L min<sup>-1</sup>, ratio 0.053 unless noted otherwise, total pressure 1 atm) entered the cell through a ¼ in. tube on one side and exited through an exhaust line on the other. The flow of each gas was regulated by MFC valves (MKS

Instruments). Millisecond time resolution was achieved by the synchronization of ethylene pulses of 30 ms duration with the forward motion of the interferometer mirror.<sup>28</sup> The spacing between ethylene pulses was 12.8 s, which assured that all reaction had ceased prior to arrival of a fresh pulse. The pulses were released through a fast valve (General Valve Series 99 pulsed valve coupled with an Iota One pulse driver) and contained 3 micromol C<sub>2</sub>H<sub>4</sub> (85 psi back pressure). The pulses merged with the continuous H<sub>2</sub>/N<sub>2</sub> flow 7 cm upstream from the center of the reactor cell. Before each series of experiments, the Pt/Al<sub>2</sub>O<sub>3</sub> catalyst was exposed for at least 2 h to a H<sub>2</sub>/N<sub>2</sub> flow at 473 K in order to assure complete reduction of the Pt surface. Ethylene (Matheson, 99.999%), hydrogen (Air Gas, 99.9999%), and nitrogen (Air Gas, 99.9995%) gas were used as received.

### 3. Results

#### 3.1 Reaction at 323 K

Survey spectra of four time slices at 25 ms resolution are shown in Figure 1. The bottom trace is the first spectrum recorded after the C<sub>2</sub>H<sub>4</sub> pulse, with its midpoint delayed by 24 ms relative to the opening of the pulsed ethylene valve. Subsequent traces shown are at 107, 235, and 6,000 ms. The most prominent bands are the gas phase absorptions of C<sub>2</sub>H<sub>4</sub> at 3000 cm<sup>-1</sup> ( $\nu_9$  and  $\nu_{11}$ ), 1890 cm<sup>-1</sup> ( $\nu_7 + \nu_8$ ), 1440 cm<sup>-1</sup> ( $\nu_{12}$ ), and 950 cm<sup>-1</sup> ( $\nu_7$ ).<sup>29</sup> The ethylene gas phase bands are the strongest in the first time slice and then decrease, principally due to removal of the reactant from the infrared viewing zone by gas flow.<sup>26</sup> The kinetics of the ethylene decrease is displayed in Figure 2. The depletion observed at



2050  $\text{cm}^{-1}$  is attributed to loss of Pt-H absorption.<sup>26</sup> The presence of CO, which also absorbs around 2050  $\text{cm}^{-1}$ , was ruled out by experiments with  $\text{D}_2$ .<sup>26</sup>

More interestingly, the survey spectra reveal additional bands at 2893, 2870, 1339, and 1200  $\text{cm}^{-1}$  whose kinetic behavior is very different from that of ethylene. These absorptions were already observed in the 100 ms spectra recorded previously at 473 K and attributed to gas phase ethane (2893  $\text{cm}^{-1}$ ,  $\nu_8+\nu_{11}$ )<sup>26,30</sup>, surface ethylidyne ( $\text{CH}_3\text{Cpt}_3$ , 2880 and 1339  $\text{cm}^{-1}$ ), and surface ethyl species ( $\text{CH}_3\text{CH}_2\text{Pt}$ , 2870 and 1200  $\text{cm}^{-1}$ ).<sup>26</sup> However, the improved sensitivity, time resolution and lower reaction temperatures reported here furnish crucial kinetic insights not accessible in our preliminary study. The ethane band at 2893  $\text{cm}^{-1}$  grows during the initial 200 ms period and then starts to decrease. Computer subtraction of  $\text{C}_2\text{H}_4$  absorption facilitates the kinetic analysis of the ethane band. Precise spectral subtraction is achieved by adjusting the intensity of the  $\text{C}_2\text{H}_4$  spectrum so that the 1890  $\text{cm}^{-1}$  band cancels completely (the region is free of overlap with any other species). The spectra are shown in Figure 3a, and the absorbance growth kinetics including a single exponential fit, in Figure 3b. Determination of the latter required that each spectral trace was corrected for the loss of product by removal through gas flow, which is evident from the observed decrease of the 2893  $\text{cm}^{-1}$  peak at times greater than 200 ms. Since the ethane molecules join the flow of the  $\text{C}_2\text{H}_4\text{-N}_2\text{-H}_2$  gas mixture upon desorption from the Pt surface, the rate of removal of  $\text{C}_2\text{H}_6$  from the viewing zone is the same as that of ethylene. Therefore, the  $\text{C}_2\text{H}_6$  band at time  $t$  was normalized by the factor  $[\text{C}_2\text{H}_4]_{24\text{msec}}/[\text{C}_2\text{H}_4]_t$  taken from Figure 2. Comparison with an authentic spectrum of gaseous  $\text{C}_2\text{H}_6$  recorded with identical spectral parameters (bottom

trace of Figure 3a) shows that the spectral subtraction reveals the  $\nu_5(\text{CH})$  mode of ethane at  $2954\text{ cm}^{-1}$  in addition to the  $2893\text{ cm}^{-1}$  band already observed in the raw spectra.<sup>30</sup> The growth of the two ethane bands is identical within uncertainties, with a  $1/e$  rise time of  $144 \pm 14\text{ ms}$ . The  $\text{C}_2\text{H}_6$  product also absorbs at  $2880\text{ cm}^{-1}$  (P branch of  $\nu_8+\nu_{11}$ ), but this band is overlapped by surface ethyl absorption in the initial time slices. Ethylidyne is also known to absorb at  $2880\text{ cm}^{-1}$ .<sup>10</sup> However, the growth of  $\text{CH}_3\text{CPT}_3$  is too small at  $323\text{ K}$  even on the hundreds of ms time scale for detecting its CH stretch absorption (see below). The surface ethyl species contribution to the spectrum in the  $\nu(\text{CH})$  region can be seen when comparing the first time slices of Figure 3a ( $t = 24$  and  $107\text{ ms}$ ), shown in Figure 4 on an expanded scale for clarity; the  $2880\text{ cm}^{-1}$  peak and the shoulder at  $2870\text{ cm}^{-1}$  in the  $24\text{ ms}$  spectrum are too strong for sole attribution to ethane, with its gas phase peak at  $2893\text{ cm}^{-1}$ . By contrast, at  $107\text{ ms}$  the  $2880$  and  $2870\text{ cm}^{-1}$  absorptions of  $\text{CH}_3\text{CH}_2\text{Pt}$  are overwhelmed completely by the  $\text{C}_2\text{H}_6$  spectrum.

Figure 5 shows the decay kinetics of the transient  $1200\text{ cm}^{-1}$  band assigned to surface ethyl species.<sup>26</sup> We find that the decay time of  $122 \pm 10\text{ ms}$  obtained from a single exponential fit (Figure 5b) is the same within error limits as the rise constant of ethane under identical  $\text{H}_2\text{-N}_2$  flow conditions. This directly demonstrates that the ethane growth originates from hydrogenation of  $\text{CH}_3\text{CH}_2\text{Pt}$  species. Moreover, the rate within a factor of 2 of the TOF over a Pt(111) surface reported for steady state experiments ( $323\text{ K}$ ,  $p_{\text{C}_2\text{H}_4} = 10\text{ Torr}$ ,  $p_{\text{H}_2} = 10\text{ Torr}$ ,  $p_{\text{N}_2} = 80\text{ Torr}$ ).<sup>31</sup> As expected, the rate of surface ethyl decay increases with increasing  $\text{H}_2$  flow, reflecting the dependence on H surface coverage. For example, the rates are  $4.1\text{ s}^{-1}$  for  $\text{H}_2/\text{N}_2 = 0.027$ , and  $8.2\text{ s}^{-1}$  for  $\text{H}_2/\text{N}_2 = 0.053$ .

In agreement with the known spectator role of ethynidyne, there is only a very small band observed at  $1339\text{ cm}^{-1}$  immediately after the ethylene pulse (Figure 6a). The species grows in with a rise time of 150 ms, as shown in Figure 6b. The finding confirms the well-known fact that the rate of formation of  $\text{CH}_3\text{CPT}_3$  is orders of magnitude lower than that of surface ethyl species.<sup>1b</sup>

### *3.2 Temperature Dependence of Surface Ethyl-to-Ethane Kinetics*

At 473 K, the ethane growth was found to reach a maximum in the first time slice after the pulse.<sup>26</sup> The most striking observations upon decrease of the reaction temperature are the gradual appearance of an ethane growth on the tens to hundreds of ms scale, and a decrease of the prompt ethane component in the first time slice. The prompt  $\text{C}_2\text{H}_6$  growth as fraction of the asymptotic growth decreases from 0.75 at 473 K to 0.44 at 323 K, as can be seen from Figure 7. Over the same temperature range from 473-323 K, the amount of surface ethyl ( $1200\text{ cm}^{-1}$ ) observed in the initial  $t = 24\text{ ms}$  time slice increases 5-fold from  $A(1200\text{ cm}^{-1}) = 0.003$  at 473 K to  $A(1200\text{ cm}^{-1}) = 0.014$  at 323 K. By contrast, the temperature dependence of the first-order rate constant of the  $\text{CH}_3\text{CH}_2\text{Pt}$  decay is rather weak, decreasing from  $6.9\text{ s}^{-1}$  at 473 to  $4.1\text{ s}^{-1}$  at 323 K ( $\text{H}_2/\text{N}_2 = 0.027$ ).

#### 4. Discussion

Our observation by time-resolved FT-IR that the rise of ethane mirrors the decay time of  $\text{CH}_3\text{CH}_2\text{Pt}$  establishes the direct kinetic evidence for the surface ethyl as the kinetically relevant intermediate. This is to our knowledge the first direct proof of the kinetic significance of an observed intermediate in a heterogeneous catalytic reaction. Our finding that surface  $\text{CH}_3\text{CH}_2\text{Pt}$  is the rate-limiting species rather than  $\pi\text{-C}_2\text{H}_4$  is supported by recent DFT calculations on ethylene hydrogenation over noble metals. The computations consistently predict the activation barrier of  $\pi$ -ethylene to ethyl hydrogenation (step 1) to be substantially lower than the ethyl hydrogenation barrier (step 2). DFT results for Pt by Miura *et al.* give  $E_{a,1}$  of  $4 \text{ kcal mol}^{-1}$ , which is much smaller than  $E_{a,2}$  of  $27 \text{ kcal mol}^{-1}$ .<sup>24</sup> A similar computational result was obtained by Neurock *et al.* for  $\text{C}_2\text{H}_4$  hydrogenation over Pd surfaces, with  $E_{a,1} = 9 \text{ kcal mol}^{-1}$  compared to  $E_{a,2} = 17 \text{ kcal mol}^{-1}$ .<sup>23</sup> We conclude that surface ethyl to ethane interconversion is the rate determining step of ethylene hydrogenation under reaction conditions. The fact that the  $\text{CH}_3\text{CH}_2\text{Pt}$  growth is complete in a few ms at all temperatures examined (323-473 K) is in agreement with the low activation energy of step 1 predicted by the DFT calculations.

Prompt growth of ethane is observed at all temperatures. As can be seen from Figure 3b, at 323 K the single exponential fit of the absorbance growth of the  $2893 \text{ cm}^{-1}$  band predicts a substantial  $\text{C}_2\text{H}_6$  yield at  $t = 0$ , about 10 percent of the asymptotic growth at that temperature. Clearly, part of the surface ethyl species react with substantially faster rates than the majority of the  $\text{CH}_3\text{CH}_2\text{Pt}$  intermediates. The most likely origin of the

dispersion of the first order rate constants is heterogeneity of the surface environment in which the reaction takes place, resulting in varying strength of interaction of the ethyl moiety with the Pt surface. The most weakly interacting intermediates are expected to exhibit the highest hydrogenation rates, the most strongly interacting ones the slowest rates. A recent computational study of C<sub>2</sub>H<sub>4</sub> hydrogenation on Pd(111) by Neurock and Van Santen revealed a strong dependence of the C<sub>2</sub>H<sub>5</sub>-Pd bond strength on surface coverage.<sup>23</sup> Specifically, if the adsorbed ethyl and an adsorbed H share a Pd center, the intermediate is destabilized by 7 kcal mol<sup>-1</sup> due to repulsive interaction, reducing the barrier of hydrogenation step 2 from 24 to 17 kcal mol<sup>-1</sup>.<sup>23</sup> A likely origin for the dispersion of the ethyl to ethane hydrogenation rates on Pt/Al<sub>2</sub>O<sub>3</sub> catalyst is therefore heterogeneity in the H distribution on the metal surface resulting in varying degree of destabilization of the C<sub>2</sub>H<sub>5</sub>Pt species. The fraction of ethyl intermediates undergoing hydrogenation prior to the 24 ms time slice is expected to increase with rising temperature at the expense of the amount of CH<sub>3</sub>CH<sub>2</sub>Pt formed, in agreement with the results of our measurements. On the other hand, the observed temperature dependence of the rate constant in the range 473–323 K is weak. This is to be expected for a limited measurement window ( $t > 24$  ms) in the case of dispersive kinetics: as the temperature is lowered, ethyl species that are hydrogenated at  $t < 24$  ms at the higher temperature become observable on the  $t > 24$  ms scale, thereby masking the rate decrease of the slower (more stable) ethyl species.

The very large temperature dependence of the intensity ratio of the 2 surface species CH<sub>3</sub>CH<sub>2</sub>Pt and CH<sub>3</sub>CPT<sub>3</sub> is worth noting. At 473 K, the 1200 cm<sup>-1</sup> peak of ethyl and the

1339  $\text{cm}^{-1}$  band of ethylidyne have the same intensity within a factor of 2, and both species exhibit the maximum buildup in the first spectrum after the pulse. By contrast, at 323 K, only the ethyl growth is complete at  $t < 24$  ms while the ethylidyne band shows a factor of 10 lower intensity in the first time slice, and grows slowly on the hundreds of ms scale. The very large decrease of the rate of formation of ethylidyne from 473 to 323 K is consistent with the high barrier estimated for ethylene to ethylidyne dehydrogenation,<sup>32</sup> and confirms the orders of magnitude slower hydrogenation rate of  $\text{CH}_3\text{Ct}_3$  compared to  $\pi\text{-C}_2\text{H}_4$  and  $\text{CH}_3\text{CH}_2\text{Pt}$ .<sup>1b</sup> The explanation for the observation of similar amounts of ethyl and ethylidyne observed in the 473 K experiment is that most surface  $\text{CH}_3\text{CH}_2\text{Pt}$  are consumed by hydrogenation to  $\text{C}_2\text{H}_6$  before the 24 ms spectrum is recorded. This results in only small amounts of ethyl species left unreacted on the tens of ms time scale.

## 5. Conclusions

FT-IR monitoring of ethylene hydrogenation over  $\text{Pt}/\text{Al}_2\text{O}_3$  with a time resolution of 25 ms in the temperature range 323 to 473 K reveals surface ethyl as the rate-limiting reaction intermediate. The hydrogenation of ethylene to  $\text{CH}_3\text{CH}_2\text{Pt}$  is instantaneous on the ms time scale at all temperatures examined, indicating a substantially lower barrier compared to surface ethyl to ethane conversion. These observations are in agreement with recent DFT calculations reported in the literature. The decay of  $\text{CH}_3\text{CH}_2\text{Pt}$  was found to exhibit the same temporal behavior as the rise of  $\text{C}_2\text{H}_6$ , demonstrating directly

the kinetic significance of the surface ethyl intermediates for the first time. Dispersive kinetics of the ethyl to ethane hydrogenation manifests the varying strength of interaction of  $\text{CH}_3\text{CH}_2$  with the Pt surface, which we attribute to heterogeneity of the surface coverage. Computational work on ethylene hydrogenation over a Pd surface by Neurock et al. suggests that the distribution of H on the metal surface is the likely cause of the variation of the ethyl-surface interaction strength. At 323 K, the rise of the ethylidyne spectator species is on the order of 200 ms, consistent with the much higher barrier of ethylene dehydrogenation compared to hydrogenation at high surface coverage. As expected, the rate of  $\text{CH}_3\text{CPT}_3$  formation increases beyond the ms resolution limit of our current experiment when raising the temperature to 473 K. While 25 millisecond time resolution using the rapid-scan technique coupled with pulsed release of reactants through a mechanical valve proved sufficient for the monitoring of ethyl to ethane hydrogenation, the microsecond and nanosecond resolution of the step-scan FT-IR technique will be required for monitoring the initial, ethylene to ethyl hydrogenation step.<sup>28</sup>

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## Figure Captions

Figure 1: Rapid-scan survey spectra of  $C_2H_4 + H_2$  reaction induced by ethylene pulses over  $Pt/Al_2O_3$  at 323 K recorded at 25 ms resolution. Times refer to the time delay between the opening of the pulsed valve and the midpoint of the corresponding interferogram slice. Spectra above  $1600\text{ cm}^{-1}$  were recorded with the 8 micron bandgap HgCdTe detector, those in the  $1600\text{--}800\text{ cm}^{-1}$  region with the 12 micron bandgap HgCdTe detector. The derivative-type signal at  $1250\text{ cm}^{-1}$  is an effect of the detector.

Figure 2: Decrease of ethylene absorption (peak intensity of the  $1890\text{ cm}^{-1}$  band) caused by gas flow. A 3 micromol  $C_2H_4$  pulse of 30 ms duration (85 psi back pressure) was released into a continuous  $H_2\text{-}N_2$  flow ( $4.5\text{ L min}^{-1}$ , 1 atm,  $H_2/N_2 = 0.053$ ) at 323 K

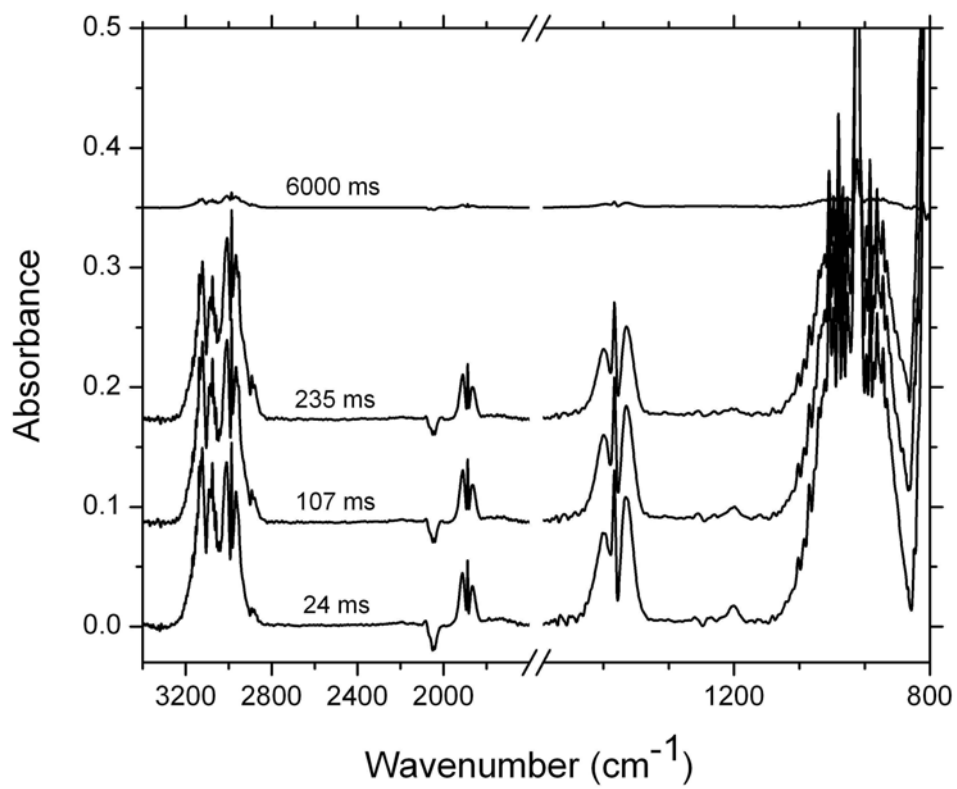
Figure 3: Rapid-scan spectra in the  $3200\text{--}2700\text{ cm}^{-1}$  region observed following the initiation of  $C_2H_4 + H_2$  catalysis at 323 K. The ethylene bands have been subtracted. The bottom trace shows the static spectrum of an authentic ethane sample recorded with the same spectral parameters used for the time-resolved  $C_2H_4 + H_2$  runs. (b) Kinetics of ethane growth (peak absorbance at  $2893\text{ cm}^{-1}$ ). The data points are corrected for absorbance loss due to removal of ethane by gas flow (see text). The solid line represents a single exponential fit.

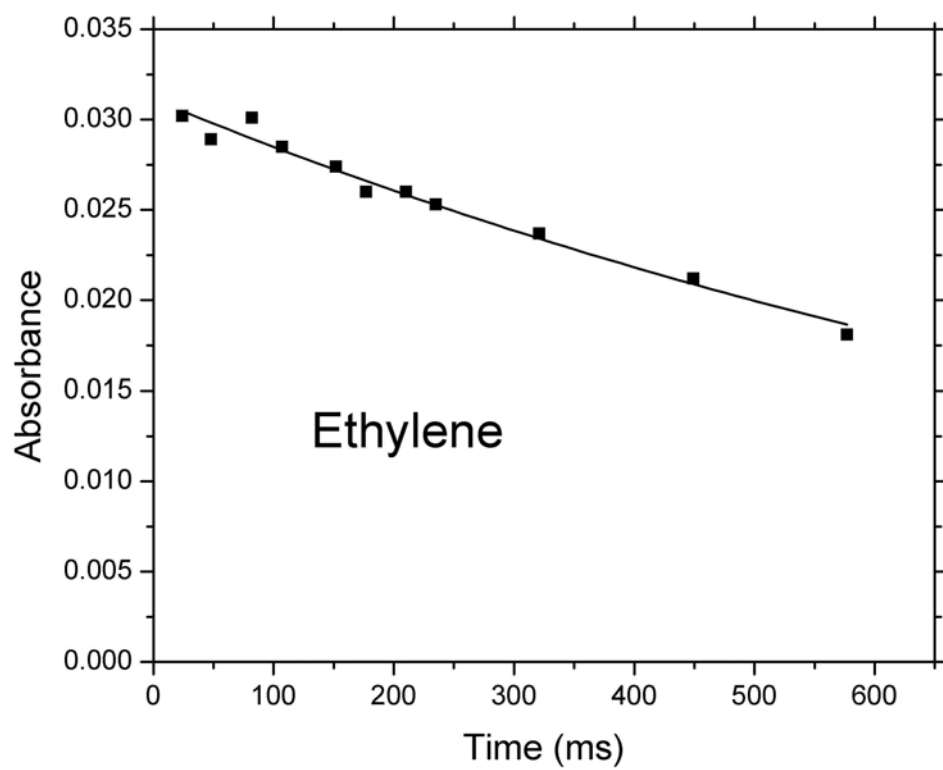
Figure 4: C-H stretch absorptions of surface ethyl and ethane at 24 and 107 ms after initiation of catalysis.

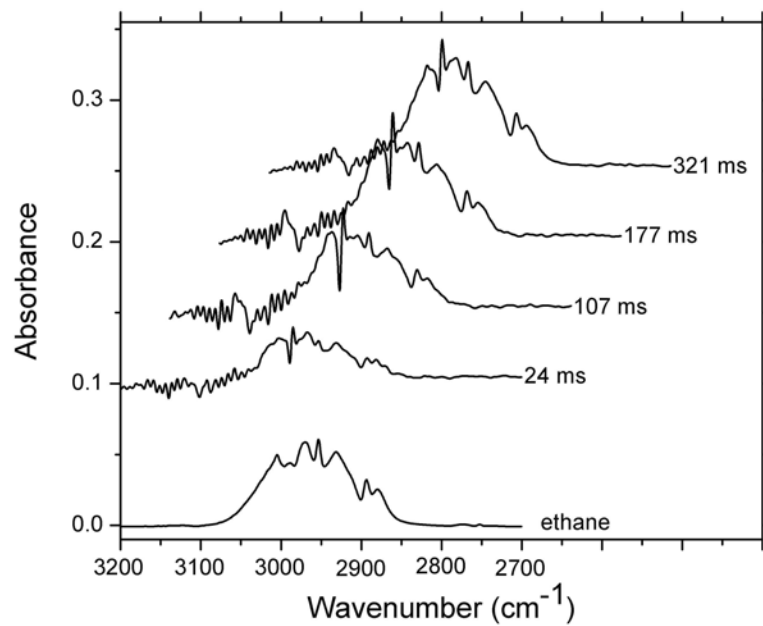
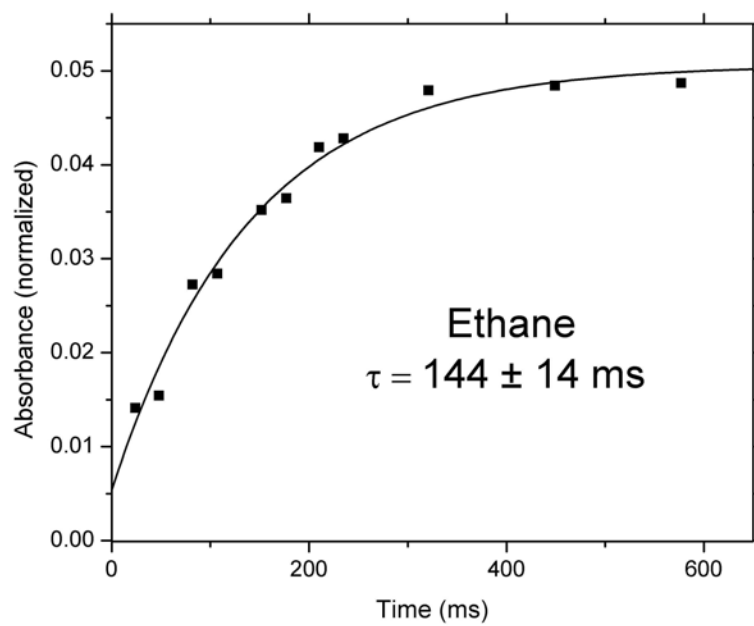
Figure 5: Rapid-scan spectra in the 1250-1120  $\text{cm}^{-1}$  region observed following the initiation of  $\text{C}_2\text{H}_4 + \text{H}_2$  catalysis at 323 K. The solid curve of panel (b) represents a single exponential fit to the peak absorbance of the 1200  $\text{cm}^{-1}$   $\text{CH}_3\text{CH}_2\text{Pt}$  band.

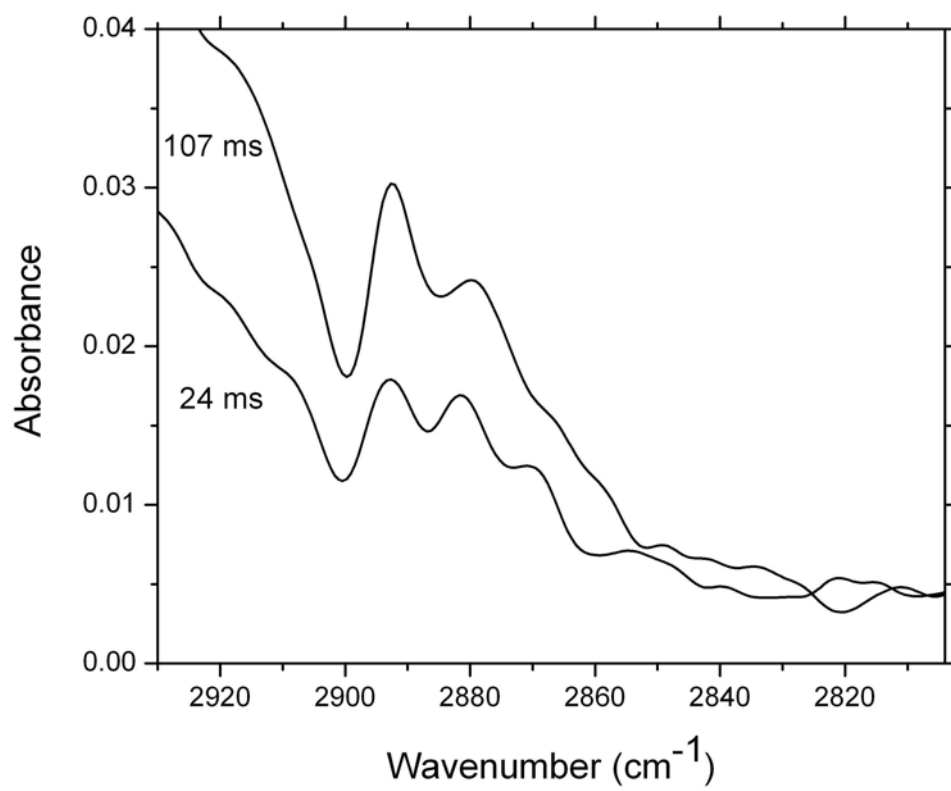
Figure 6: Rapid-scan spectra in the 1375-1275  $\text{cm}^{-1}$  region observed following the initiation of  $\text{C}_2\text{H}_4 + \text{H}_2$  catalysis at 323 K. A:  $t = 36$  ms; B:  $t = 164$  ms; C:  $t = 321$  ms; D:  $t = 577$  ms.

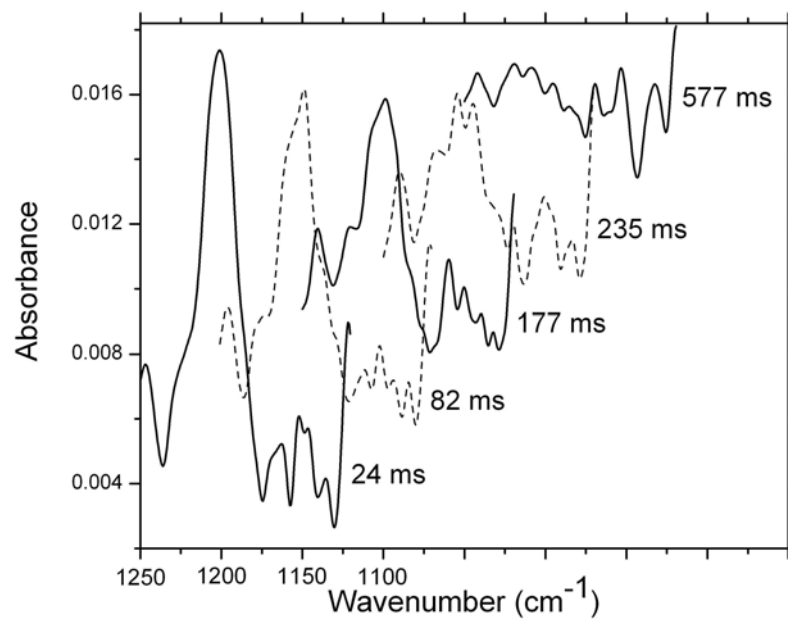
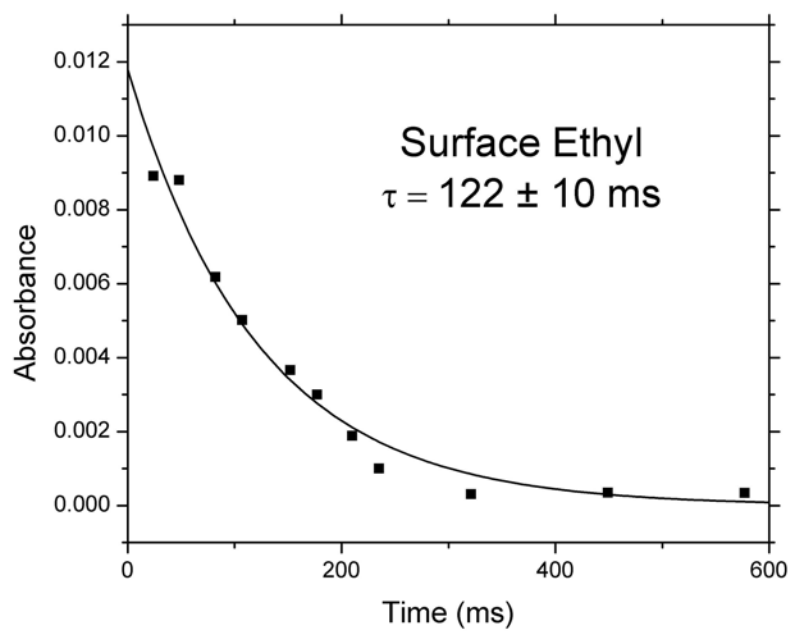
Figure 7: Prompt growth of ethane upon  $\text{C}_2\text{H}_4$  hydrogenation as function of temperature. The ratio corresponds to the ethane absorbance of the first time slice (24 ms) relative to the asymptotic  $\text{C}_2\text{H}_6$  growth (2893  $\text{cm}^{-1}$ ). Data shown used a flow of 9  $\text{L min}^{-1}$  and a  $\text{H}_2/\text{N}_2$  ratio of 0.027.

**Figure 1**

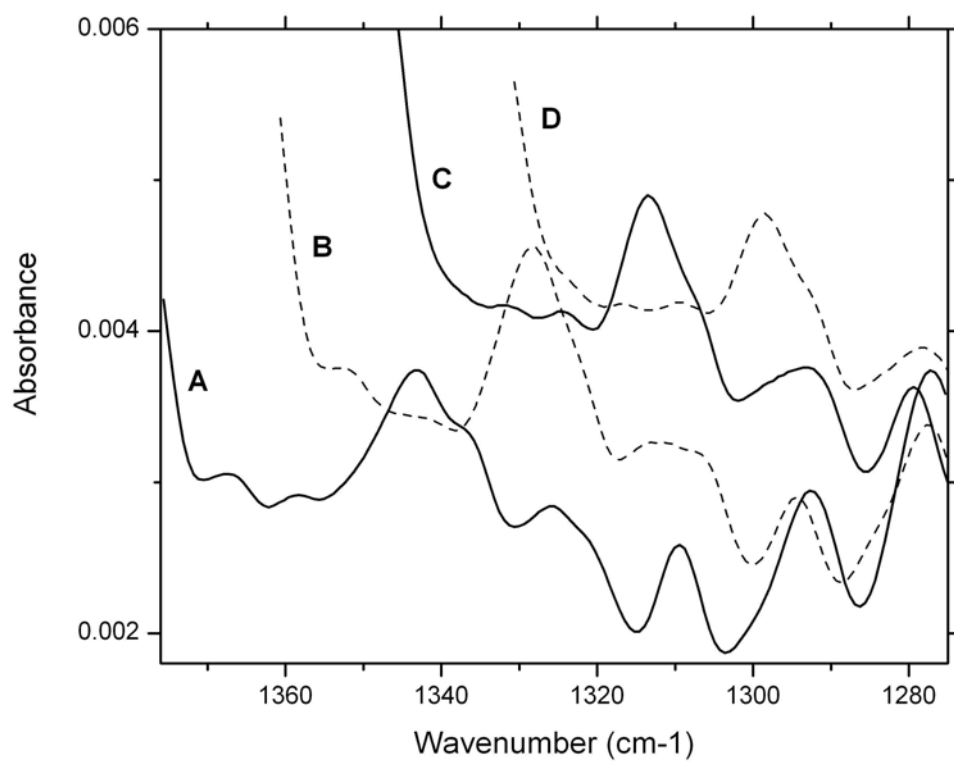
**Figure 2**

**Figure 3a****Figure 3b**

**Figure 4**

**Figure 5a****Figure 5b**



**Figure 6**

**Figure 7**