

**Molecule-Substrate Vibration of CO on Ni(100) Studied by Infrared-Emission Spectroscopy**

S. Chiang,<sup>(a)</sup> R. G. Tobin, P. L. Richards, and P. A. Thiel<sup>(b)</sup>  
*Department of Physics, University of California, Berkeley, California 94720, and  
Materials and Molecular Research Division, Lawrence Berkeley Laboratory,  
Berkeley, California 94720*

(Received 11 October 1983)

A novel infrared-emission technique has been used to make the first measurement of the linewidth of a molecule-substrate vibrational mode on a well characterized single-crystal surface. At saturation coverage, the observed linewidth of the C-Ni mode of CO on Ni(100) is  $15\text{ cm}^{-1}$ . This result is in agreement with predictions for broadening due to deexcitation by two-phonon emission.

PACS numbers: 68.45.By; 63.20.-e, 78.30.-j

The usefulness of vibrational spectroscopy in the identification of surface species, the determination of adsorbate structures, and the study of dynamical processes has been thoroughly demonstrated.<sup>1</sup> Although electron energy-loss spectroscopy (EELS) has been a popular technique because of its inherently high surface sensitivity and large spectral range, its relatively poor resolution of 30 to  $100\text{ cm}^{-1}$  makes the measurement of linewidths and line shapes extremely difficult.<sup>2</sup> Infrared spectroscopists find it easy to obtain resolution less than  $5\text{ cm}^{-1}$ , but have had to struggle for adequate sensitivity. They have generally been unable to observe modes at frequencies less than  $1000\text{ cm}^{-1}$ .<sup>3</sup>

Infrared-emission spectroscopy offers certain advantages over other types of infrared surface spectroscopy in sensitivity and versatility. For substrates that are not strongly absorbing, such as metals, it provides a reduction in background, compared to reflection-absorption spectroscopy. The method is equally applicable to smooth or rough surfaces, can be used with transparent substrates as well as metals, and can be used with high pressures and elevated sample temperatures. Several groups have previously used infrared emission to study adsorbed monolayers,<sup>4</sup> but our experiment is the first to apply the technique to submonolayer coverages of adsorbates on well characterized single-crystal metal surfaces in ultrahigh vacuum. Our apparatus is also the first to extend the infrared spectroscopy of single-crystal surfaces into the frequency range of a few hundred  $\text{cm}^{-1}$ , which contains important adsorbate-substrate modes. Sample configurations different from ours would be required or preferred in order to use emission spectroscopy to study systems other than metal surfaces in vacuum.

The infrared-emission apparatus that we have developed uses a liquid-helium-temperature

grating spectrometer to measure the radiation from a sample in thermal equilibrium near room temperature. Since a detailed description of the apparatus is to be published elsewhere,<sup>5</sup> we give only a brief summary of the technique here. Figure 1 shows a diagram of the apparatus. The Ni(100) sample was mounted on a manipulator in an ultrahigh-vacuum chamber, with a base pressure of  $10^{-10}$  Torr, which was equipped with conventional surface preparation and characterization facilities. It was cleaned by argon-ion sputtering to remove sulfur, by heating to  $800^\circ\text{C}$  for annealing, and by oxygen treatments to remove residual carbon. The best indicator of sample cleanliness was the observation of a sharp  $c(2\times 2)$  low-energy electron diffraction (LEED) pattern when the surface was saturated with CO. During infrared measurements, the sample temperature was held constant within  $\pm 0.05\text{ K}$  at approximately  $310\text{ K}$ .

Thermal radiation emitted by the sample is focused by a lens onto the entrance slit of the spectrometer. The light is collimated, diffracted from a grating, and refocused onto an Si:Sb photoconductive detector. Liquid-nitrogen-temperature baffles around the sample provide contrast to observe the sample emission, and the spectrometer is maintained at  $5\text{ K}$  to minimize infrared background radiation. The present experiments are made in the dc mode and are limited by slow drifts. Significant improvements in signal-to-noise ratio, potentially by a factor of 10–100, may be achieved by implementing an appropriate modulation.<sup>5</sup>

A reference spectrum of the clean nickel surface is first measured by recording the detector signal as a function of the grating position, which is under computer control. After the sample has been dosed with CO, its emission spectrum is measured again. The ratio of the spectrum of Ni with CO to the reference spectrum is computed

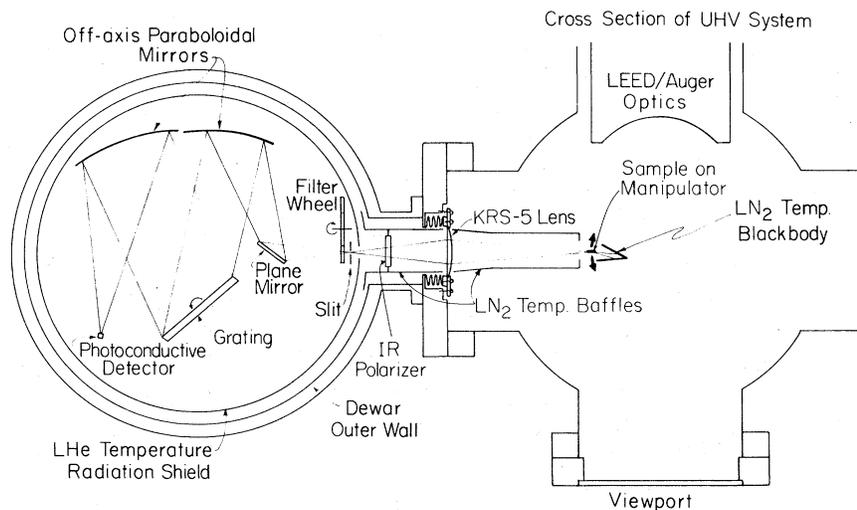


FIG. 1. Optical layout of the infrared emission apparatus, with liquid-helium-cooled spectrometer on the left and ultrahigh-vacuum system on the right.

to obtain the adsorbate spectrum. Wavelengths are measured relative to the 24th-order diffraction of light from a He:Ne laser.

Figure 2 shows infrared-emission spectra from a Ni(100) surface saturated with CO at room temperature, in the frequency range of the molecule-substrate mode. The two curves were measured with different sample preparation procedures. In both cases a sharp  $1 \times 1$  LEED pattern was observed before the sample was dosed with CO. Curve *a* was obtained from a disordered CO layer

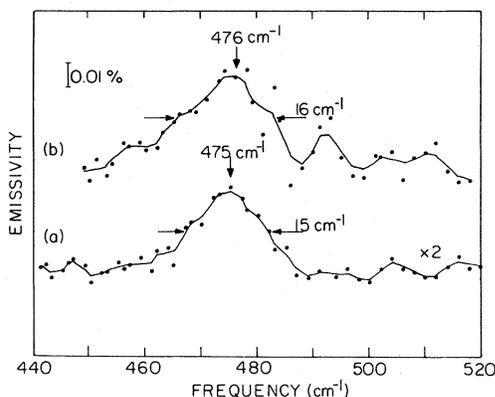


FIG. 2. Infrared emission spectra from a saturation coverage of CO on Ni(100) at 310 K. The instrumental resolution was  $2.5 \text{ cm}^{-1}$ , and a linear baseline has been subtracted from the curves. The solid lines are obtained by computer smoothing of the data. Curve *a*, spectrum of a disordered CO layer on a partially contaminated surface. Curve *b*, spectrum of an ordered  $c(2 \times 2)$  CO overlayer on a clean surface.

on a surface with significant residual contamination. The  $c(2 \times 2)$  LEED pattern expected for CO on clean Ni(100) was not seen. Infrared-emission spectra measured in the C=O stretch-frequency range showed that for this surface the CO was in bridge-bonded as well as linearly bonded sites.<sup>6</sup> The data in curve *a* represent the average of thirty spectra from five separate experimental runs, with a total integration time per point of 30 sec. The peak frequency of  $475 \pm 5 \text{ cm}^{-1}$  is in good agreement with EELS results.<sup>7</sup> The line is well resolved; the observed linewidth (full width at half maximum) is  $15 \pm 1 \text{ cm}^{-1}$ , while the instrumental resolution is approximately  $2.5 \text{ cm}^{-1}$ . The greater uncertainty in the peak frequency is due to errors in the absolute calibration of the grating angle.

Curve *b* was measured after refined cleaning procedures had improved the state of the surface. Although our available Auger system could not distinguish between the two surfaces, thermal-desorption spectroscopy showed that the surface used for curve *b* had significantly less surface carbon. A sharp  $c(2 \times 2)$  LEED pattern was observed when a saturation dose of CO was added. Spectra from the C=O stretch range showed only linearly bonded CO as is expected for the ideal  $c(2 \times 2)$  structure. The absence of the bridge-bonded CO suggests that this surface was significantly cleaner than those previously used for vibrational studies of the CO/Ni(100) system.<sup>7,8</sup> The spectrum shown in curve *b* represents a single experimental run, and a total of 10 sec of

integration per point. The signal-to-noise ratio for curve *b* is significantly less good than for curve *a*. The feature at  $490\text{ cm}^{-1}$  in curve *b*, for example, is likely to be noise.

The peak frequencies and the linewidths of the two spectra are the same, within experimental error. For the ordered  $c(2\times 2)$  overlayer (curve *b*), the peak frequency is  $476 \pm 5\text{ cm}^{-1}$ , and the linewidth is  $16 \pm 2\text{ cm}^{-1}$ . The intensity of the line is about a factor of 2 greater in curve *b* than that observed in curve *a*. The difference could arise from incomplete surface coverage in the disordered case, or from better sample positioning for the spectrum of the ordered overlayer. Using the theory described by Ibach,<sup>9</sup> suitably adapted for our experiment, and assuming a rigid surface, we calculate a screened effective charge for the  $c(2\times 2)$  layer of  $e^* = 0.17$ , in reasonable agreement with Ibach's<sup>9,10</sup> published value of  $e^* = 0.21$ .

The spectra in Fig. 2 represent the first measurements of the linewidth of the low-frequency adsorbate-substrate mode of a molecular adsorbate on a well characterized single-crystal metal surface. They strikingly demonstrate the ability of our infrared-emission technique to bring high resolution and monolayer or submonolayer sensitivity to a wide range of vibrational frequencies. Previous measurements of such modes for molecular adsorbates have been made only with high surface area polycrystalline samples.<sup>11-13</sup> The only infrared measurements of adsorbate-substrate modes on single-crystal surfaces have used atomic hydrogen, which has a high vibrational frequency, and have relied on special properties of the experimental system in order to obtain adequate sensitivity. The vibration of hydrogen on tungsten (100) was measured with a technique that exploited the coincidence of the vibrational frequency with a  $\text{CO}_2$  laser band.<sup>14</sup> An internal reflection geometry, useful for transparent substrates, has been used to resolve the vibration of hydrogen on single-crystal silicon.<sup>15,16</sup>

Our instrument has also been used<sup>6,17</sup> to obtain spectra with excellent signal-to-noise ratio in the higher frequency range of the carbon-oxygen stretching vibration of CO, at  $\sim 2000\text{ cm}^{-1}$ . It easily measures signals from as little as 0.05 monolayer of CO in 1 min, with a resolution of  $15\text{ cm}^{-1}$ . Improved resolution would result in some loss in sensitivity.

For relatively high-frequency intramolecular modes, such as the carbon-oxygen vibration of adsorbed CO, the most plausible explanation for

the observed linewidths seems to be the coupling of the vibration to the electrons in the metal, via an adsorbate-induced resonance in the density of states at the Fermi level.<sup>18</sup> Because the volume of momentum space accessible to the electron-hole pairs is proportional to the vibrational energy, and because the absorption strength is believed to be related to the degree of vibrational coupling to the electron gas, it is expected from this model that the carbon-metal stretching vibration, with its lower frequency and intensity, would be much narrower than the C=O stretching mode. In fact, however, the modes have comparable widths, which suggests that other mechanisms dominate the width of the carbon-metal vibration.

Three other line-broadening processes must be considered. Inhomogeneous broadening cannot be absolutely excluded. The measurement of the same linewidth for a well ordered  $c(2\times 2)$  overlayer as for a disordered layer minimizes the likelihood of disorder-induced broadening, but a more direct demonstration that the linewidth is intrinsic—for example, by measuring the temperature dependence of the linewidth—is certainly important, and will be attempted.

A second possibility is that the linewidth is dominated by the dephasing process, in which variations in the phase of vibration of an excited molecule, due to elastic collisions with phonons, broaden the line without shifting its frequency.<sup>19</sup> Persson has estimated that the broadening due to dephasing should be 30 times smaller than that due to deexcitation by phonon emission, for the C-Ni mode in question.<sup>20</sup>

Vibrational decay by the excitation of substrate phonons is not important for the C=O stretching vibration,<sup>21</sup> but it is expected to be more important at lower frequencies. Since the maximum phonon frequency of bulk nickel<sup>22</sup> is  $\sim 300\text{ cm}^{-1}$ , the  $\sim 2000\text{-cm}^{-1}$  intramolecular mode must decay via at least a seven-phonon process. The  $475\text{-cm}^{-1}$  molecule-substrate mode, however, can decay by the emission of only two phonons. Ariyasu *et al.*<sup>23</sup> have calculated the linewidth due to the two-phonon process, for the C-Ni mode of CO on Ni(100) at 300 K, and found a value of  $13.9\text{ cm}^{-1}$ , in excellent agreement with our experimental value. Their calculation also predicts a linear temperature dependence for the linewidth above 300 K. We will test this prediction in future experiments.

In summary, we have advanced the technique of infrared-emission spectroscopy for surface vi-

brational studies by applying it to adsorbates on well characterized single-crystal metal surfaces, and by extending it into the important frequency range of a few hundred reciprocal centimeters. We have made the first measurement of the linewidth of the molecule-substrate vibrational mode of  $c(2 \times 2)$ CO on Ni(100). The observed linewidth appears to be explained by a process of vibrational damping by two-phonon emission, in contrast to the electronic mechanism that seems to dominate at higher frequencies. Experiments to verify the decay mechanism are in progress. We expect that the data presented here, and future measurements of adsorbate-substrate modes, will stimulate further discussion and understanding of the important broadening mechanisms involved.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

<sup>(a)</sup>Present address: IBM Research Laboratory, 5600 Cottle Road, San Jose, Cal. 95193.

<sup>(b)</sup>Present address: Department of Chemistry, Iowa State University, Ames, Iowa 50011.

<sup>1</sup>*Vibrational Spectroscopy of Adsorbates*, edited by R. F. Willis (Springer-Verlag, Berlin, 1980).

<sup>2</sup>H. Ibach and D. L. Mills, *Electron Energy Loss Spectroscopy and Surface Vibrations* (Academic, New York, 1982).

<sup>3</sup>F. Hoffmann, *Surf. Sci. Rep.* **3**, 197 (1983).

<sup>4</sup>J. F. Blanke, S. E. Vincent, and John Overend, *Spectrochim. Acta* **32A**, 163 (1976); D. Kember, D. H. Chenery, N. Sheppard, and J. Fell, *Spectrochim. Acta*

**35A**, 455 (1979); M. Primet, P. Fouilloux, and B. Imelik, *Surf. Sci.* **85**, 457 (1979), and *J. Catal.* **61**, 553 (1980); L. M. Gratton, S. Paglia, F. Scattaglia, and M. Cavallini, *Appl. Spectrosc.* **32**, 310 (1978); D. L. Allara, D. Teicher, and J. F. Durana, *Chem. Phys. Lett.* **84**, 1 (1981).

<sup>5</sup>S. Chiang, R. G. Tobin, and P. L. Richards, to be published.

<sup>6</sup>R. G. Tobin, S. Chiang, P. A. Thiel, and P. L. Richards, to be published.

<sup>7</sup>S. Andersson, *Solid State Commun.* **21**, 75 (1977); J. C. Bertolini and B. Tardy, *Surf. Sci.* **102**, 131 (1981).

<sup>8</sup>M. J. Dignam, in *Vibrations at Surfaces, Proceedings of the International Conference at Namur, Belgium* edited by R. Caudano, J. M. Gilles, and A. A. Lucas (Plenum, New York, 1982), p. 265.

<sup>9</sup>H. Ibach, *Surf. Sci.* **66**, 56 (1977).

<sup>10</sup>A. M. Baro, H. Ibach, and H. D. Bruchmann, *Surf. Sci.* **88**, 384 (1979), Ref. 25.

<sup>11</sup>R. P. Eischens and W. A. Pliskin, *Adv. Catal.* **10**, 1 (1958).

<sup>12</sup>C. W. Garland, R. C. Lord, and P. F. Troiano, *J. Phys. Chem.* **69**, 1188 (1965).

<sup>13</sup>H. C. Eckstrom, G. G. Possley, S. E. Hannum, and W. H. Smith, *J. Chem. Phys.* **52**, 5435 (1970).

<sup>14</sup>Y. J. Chabal and A. J. Sievers, *Phys. Rev. Lett.* **44**, 944 (1980).

<sup>15</sup>G. E. Becker and G. W. Gobeli, *J. Chem. Phys.* **38**, 2942 (1963).

<sup>16</sup>Y. J. Chabal, *Phys. Rev. Lett.* **50**, 1850 (1983).

<sup>17</sup>S. Chiang, R. G. Tobin, and P. L. Richards, *J. Electron. Spectrosc. Relat. Phenom.* **29**, 113 (1983).

<sup>18</sup>B. N. J. Persson and M. Persson, *Solid State Commun.* **36**, 175 (1980).

<sup>19</sup>Thomas F. George, Jui-teng Lin, Kai-Shue Lam, and Cheng-hui Chang, *Opt. Eng.* **19**, 100 (1980).

<sup>20</sup>B. N. J. Persson, to be published.

<sup>21</sup>Horia Metiu and William E. Palke, *J. Chem. Phys.* **69**, 2574 (1978).

<sup>22</sup>R. J. Birgeneau, J. Cordes, G. Dolling, and A. D. B. Woods, *Phys. Rev.* **136**, A1359 (1964).

<sup>23</sup>J. C. Ariyasu, D. L. Mills, K. G. Lloyd, and J. C. Hemminger, *Phys. Rev. B* **28**, 6123 (1983).