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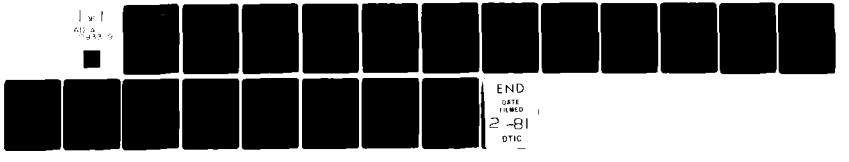

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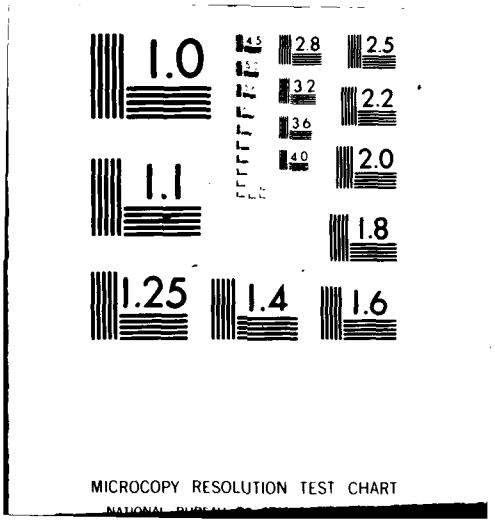
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Surface Enhanced Raman Scattering from Pyridine on Ag(111)

by

P.N. Sanda, J.M. Warlaumont, J.E. Demuth, J.C. Tsang, K. Christmann, and J.A. Bradley

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We report the first ultrahigh vacuum study of surface enhanced Raman scattering from pyridine adsorbed on a clean well-defined single-crystal silver surface. The surface contains a smooth modulation (1 micron periodicity) to allow optical coupling to surface plasmon polaritons. A large mode-selective enhancement (~10^6) of the Raman signal from the first monolayer is observed at surface plasmon polariton resonance. Coverages greater than 1 monolayer show a smaller enhancement (~10

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Surface Enhanced Raman Scattering from Pyridine on Ag(111)†

P.N. Sanda, J.M. Warlaumont, J.E. Demuth, J.C. Tsang, K. Christmann,* and J.A. Bradley

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Abstract: We report the first ultrahigh vacuum study of surface enhanced Raman scattering from pyridine adsorbed on a clean single-crystal silver surface containing a smooth modulation (1 micron periodicity) to allow optical coupling to surface plasmon polaritons. A large mode-selective enhancement ($\sim 10^4$) of the Raman signal from the first monolayer is observed at surface plasmon polariton resonance. Coverages greater than 1 monolayer show a smaller enhancement ($\sim 10^2$).

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Surface enhanced Raman scattering has been observed in electrochemical cell systems,[1] tunnel junction structures,[2,3] discontinuous films,[4] small particles in solution,[5] and recently for surfaces prepared in ultra-high vacuum (UHV).[6-8] Recent UHV experiments have used the photoreaction of iodine on Ag to form silver balls,[6] films evaporated at low temperatures,[7] or sputter-damaged polycrystalline samples.[8] However, all experiments reported including those performed in UHV have required deliberate roughening of the surface in order to obtain a measureable signal from a monolayer of an adsorbate, thereby complicating the interpretation of these results.

Here we present surface Raman scattering results using a clean, essentially (111) oriented Ag surface with a controlled surface modulation (wavelength=10,000Å). This surface contains a small amplitude, approximately sinusoidal modulation (height~1,000Å), which provides a well-defined surface periodicity to allow optical coupling to surface plasmon polaritons, while maintaining minimal deviation from a flat Ag(111) surface. Our experiments are thereby intended to ellucidate the role of surface plasmon polaritons in surface enhanced Raman scattering. We find a large enhancement ($\sim 10^4$) for the first adsorbed layer, and a comparatavely small enhancement ($\sim 10^2$) for further condensed layers. These results demonstrate that such surface plasmon polariton induced Raman scattering is strongly localized to the first molecular layer.

The experiments were performed in an ion- and Ti-sublimator-pumped vacuum system (typical base pressure of $2x10^{-10}$ Torr) having facilities for low energy electron diffraction (LEED), auger electron spectroscopy (AES), and Ar^+ sputtering. Reagent grade pyridine was used. The Raman spectra shown here were measured at 80K with the 5145 Å line from an Ar^+ laser, although measurements were also made with the 4880 Å Ar^+ line and the 5309 Å line from a Kr^+ laser. Standard backscattering geometry was used, with light collected over a solid angle of 45°. The scattered light was analyzed by a conventional double grating monochromator operating at 6 cm^{-1} resolution. Given our operating conditions, the threshold enhancement for detecting a monolayer was $\sim 5x10^2$.

Although AES was used to monitor and characterize surface cleanliness, uv-photoemission (UPS) was utilized to calibrate relative adsorbate coverages and to allow a clear delineation between chemisorbed and physisorbed pyridine. These measurements were performed in a separate vacuum system, on the same Ag crystal, using a differentially pumped He-resonance lamp ($h\nu$=21.2eV) and a double-pass cylindrical mirror analyser.[9]

The Ag crystal was spark cut, mechanically polished, chemically polished (chromic acid and HCl[10]), then several UHV sputtering/annealing cycles were used to remove C and S impurities from the bulk and to segregate dislocation defects to the surface. A final chemical polish left the crystal with a mirror-like finish, free of etch pits. The 10,000 Å periodic surface modulation was

then fabricated into a 4 x 4 mm area of the 8 x 6 mm face of the crystal, with the modulation wavevector $\vec{K}_s$ oriented along the (110) direction. This structure was fabricated by first creating a photoresist pattern on the sample using X-ray lithography techniques followed by chemical polishing to remove about 3000 Å of material in the unmasked regions (50%). The photoresist was then dissolved and the sample was repeatedly argon sputter-etched and annealed in UHV (T~500K). This preparation also served to reduce the higher order fourier components[11] of the profile, resulting in a sinusoidal-like surface (valleys slightly wider than the peaks) with a 10,000 Å wavelength and ~1000 Å height as estimated by the LEED beam profiles. The modulated region of the sample showed a well-defined, low background LEED pattern, comparable to the control region of the sample. Satellite lobes were observed in the beam profiles, which indicated a distribution of steps and terraces parallel to $\vec{K}_s$. The peak in this distribution corresponded to a terrace width to step height ratio of about 10 to 1. The intensity of the main peak relative to the side lobes indicated that roughly 90% of the surface is of (111) orientation. Although such LEED features serve as a guide to the general nature and condition of the surface, they do not provide specific information concerning all types of defects that may exist on an atomic scale.

UPS difference curves, $\Delta N(E)$, in Fig.1 show the adsorbate induced changes in emission for consecutive pyridine exposures. The ionization features in Fig.1 demonstrate a pronounced energy shift starting at coverages

above ~1.2L. This increase in binding energy for physisorbed pyridine compared to chemisorbed pyridine is expected. It is attributed to a reduction of the relaxation effects due to molecular polarization, charge transfer, and final state image charge screening for the physisorbed layer.[13] This shift can be most reliably seen (light vertical lines) in the lower lying levels (binding energy ~ 11.5 and 13 eV) which should be least affected by initial state chemical bonding effects. The absolute coverage calibration was obtained by taking the total adsorbate-induced intensity of the large peak at about 11.5 eV (combination of a_1 and b_2 orbitals)[14] to correspond to one monolayer at 1.2L exposure.

In order to obtain surface Raman scattering signals, it was necessary to couple to surface plasmon polaritons[2] by varying the orientation of the incident radiation with respect to $\vec{K}_s$. For the data presented here, we used p-polarized incident radiation and oriented the sample so that $\vec{K}_s$ was in the plane of incidence. The angle of incidence was set to the minimum in intensity of the direct reflected beam, which corresponds to maximal surface plasmon polariton excitation. The Raman scattered signal for pyridine adsorbed on the modulated portion of the sample was observed as the incident angle was brought to within 5° of this condition. As expected, there was no Raman scattered signal observed from the flat (control) portion of the sample.

The features found to be observable in the Raman spectrum for chemisorbed pyridine on our modulated Ag(111) surface occurred between 950 and

1050 cm^{-1}. No C-H modes were seen. The carbon ring deformation modes in the 1300 to 1600 cm^{-1} range could not be detected. Such features are probably masked by the broad peaks at 1350 and 1550 cm^{-1} due to trace amounts of amorphous carbon.[15,16] We found these peaks to persist even at carbon levels undetectable by AES. Also, prior to complete annealing, we observed an additional peak at 986 cm^{-1} which we associate with pyridine bound to step sites.

Representative surface Raman spectra for increasing pyridine exposures are shown in the inset in Fig.2. Compared to the liquid phase spectra, for which the symmetric (991 cm^{-1}) and the asymmetric (1030 cm^{-1}) ring breathing modes are of about equal intensity, these spectra show selective enhancement of the symmetric ring breathing mode for chemisorbed pyridine. It is not until thick condensed layers are obtained (exposure >20L) that the asymmetric ring-breathing mode starts to be observed and continues to grow with increasing exposure.

The coverage dependent Raman intensity $I(\Theta)$ of the 990 cm^{-1} (Fig.2) peak shows a dramatic increase for the first monolayer relative to higher coverages. The incremental enhancement given by $dI/d\Theta$ is plotted against Θ in Fig.3; the solid points were obtained experimentally, while the open points correspond to theory as discussed below. The enhancement for the first layer is $\sim 10^4$ from comparative Raman measurements with liquid pyridine, using the same optics and operating conditions and assuming the liquid phase packing

density for chemisorbed pyridine. $dI/d\Theta$ drops off quite rapidly in the region from $\Theta=1$ to 2 monolayers, and for larger values of Θ levels off to an asymptotic value of ~3% of the monolayer value.

A theoretical model by Kirtley, Jha and Tsang[17] predicts two mechanisms contributing to the surface enhanced Raman scattering process for a molecule adsorbed on a sinusoidal grating. 1) There is a long-range contribution, extending several thousand angstroms away from the surface, which is due to enhancement of the direct scattering intensity by the large electric field at surface plasmon polariton resonance.[18] This classical field enhancement is predicted by the theory to provide an enhancement of the Raman signal by a factor of 10^2 to 10^4. 2) The second term is associated with a short-range mechanism, which is very localized to the surface region. This effect arises from the large oscillating charge density in the molecular layer at surface plasmon polariton resonance, which is modulated by the molecular vibrations to produce a modulated surface dipole moment. This term represents a Raman scattering process with a surface plasmon polariton intermediate state. At atomic distances, the theory predicts the total combined Raman enhancement factor to be between 10^4 and 10^6.

We have compared our results to the distance dependent theory, assuming the uniform bulk packing density for pyridine. In Fig.3 we have scaled the short range and long range parts of the theoretical contribution (open circles) to the experimental values (closed circles) at $\Theta=1$ and $\Theta=20$, respectively.

Our coverage-dependent results qualitatively agree with this theory. However, due to our limits of sensitivity, we cannot exclude additional short range enhancements ($\gtrsim 10^2$) associated with mechanisms not involving surface plasmons. One proposed origin for the short range enhancement is associated with bonding to isolated Ag atoms.[7] We do not expect an appreciable density of such adatom sites after annealing our surface. Our results also differ from the weak distance dependence observed by Rowe et. al.[6] This difference may arise from the possibility that the electric field at their 1000Å balls is stronger than the field at our weakly modulated surface, which would suggest a larger classical field enhancement for their system.

In conclusion, by studying pyridine adsorption on an essentially (111) oriented Ag surface with a well-defined surface topography, we have obtained experimental results showing that surface plasmon polariton excitations can contribute to a large surface enhanced Raman scattering signal for certain adsorbate modes. The enhancement we observe is strongly distance dependent, being 10^4 for the chemisorbed pyridine and a factor of ~100 weaker for subsequent pyridine layers.

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Figure Captions

Fig.1. UPS difference spectra $\Delta N(E)$ for pairs of successive pyridine exposures, as indicated to the right. $1L = 10^{-6}$ Torr-sec, where the ion gauge pressure reading has been divided by 5.8 to account for the gauge correction (Ref. 12). Spectra e-h have been divided by 2.

Fig.2. Raman intensity vs. pyridine coverage Θ for the 990 cm^{-1} mode. One monolayer equivalent occurs at 1.2L exposure as described in the text. Inset: Raman spectra for increasing pyridine exposures: (a) 1.7L, (b) 3.4L, (c) 6.9L, (d) 19.3L, (e) 44L. The incident laser power is 150 mW.

Fig.3. Incremental enhancement factor $dI/d\Theta$, as a function of coverage as determined from Fig.2 (solid circles) and predicted by theory (open circles, Ref. 17). For modeling the theoretical distance dependence we used a pyridine interlayer spacing of 5Å (Ref. 19) and a Ag-pyridine barrier height of .25V (Ref.17).

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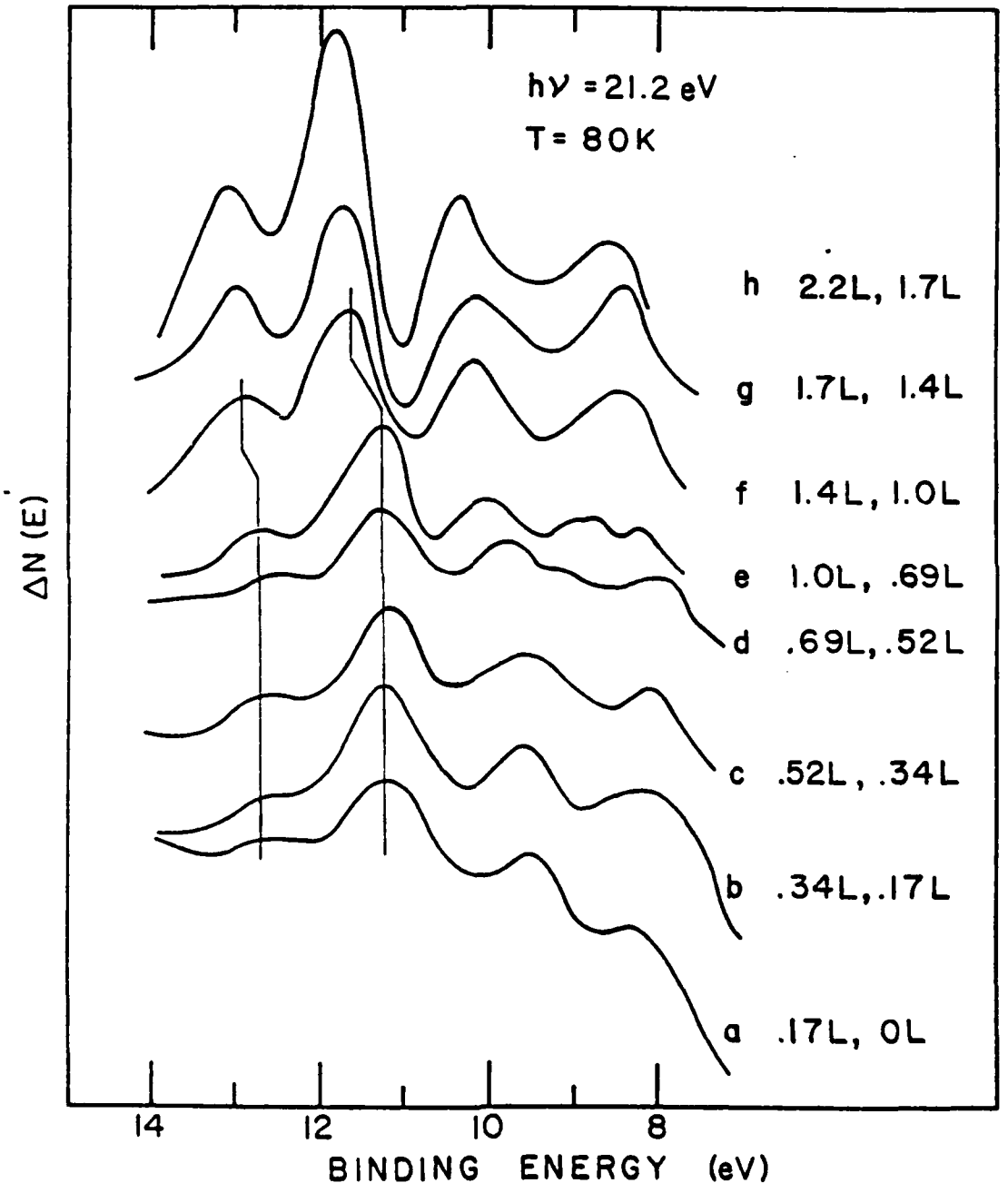
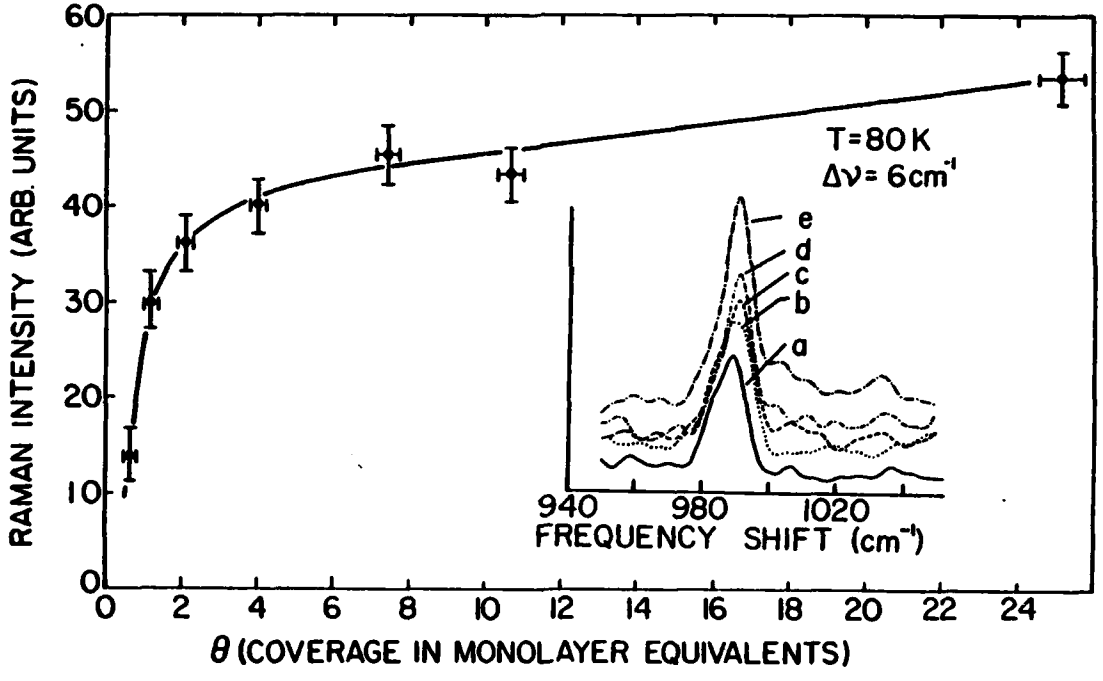


Sanda et al
fig 1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θ (COVERAGE IN MONOLAYER EQUIVALENTS)
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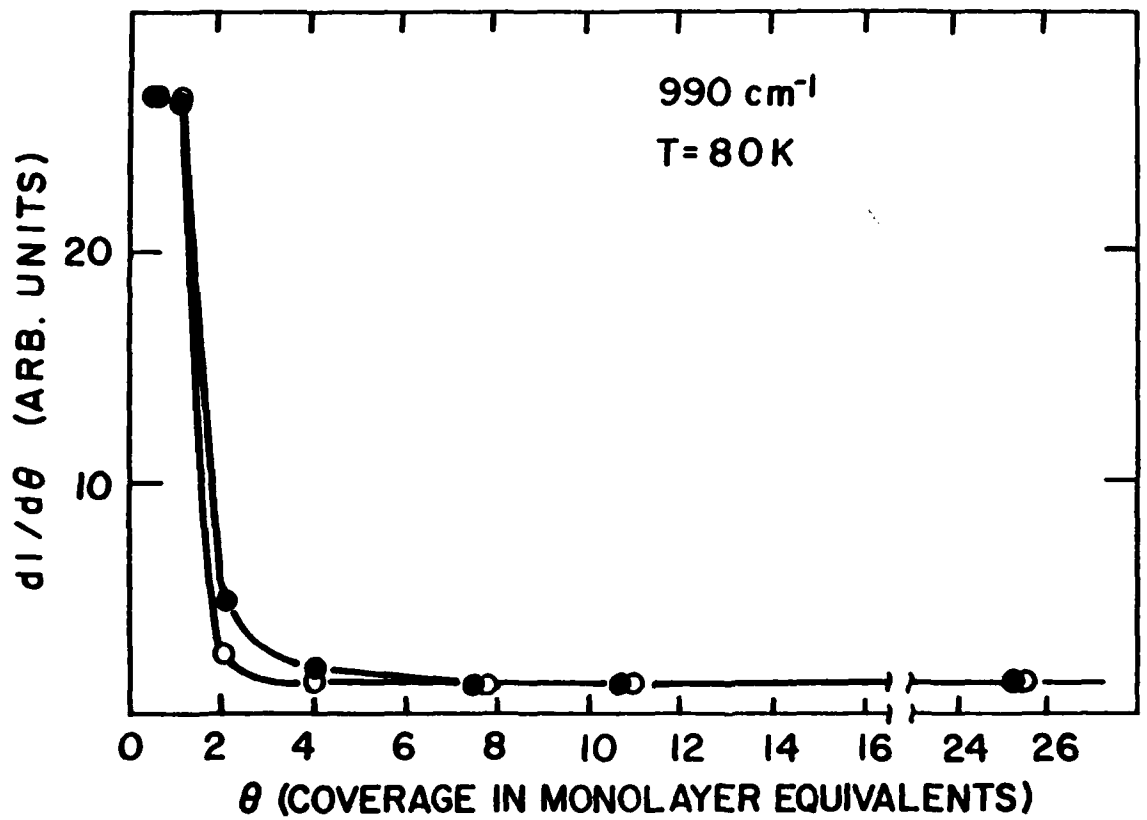
1020
FREQUENCY SHIFT (cm⁻¹)

Fig 2


990 cm⁻¹
T=80K
dI/dθ (ARB. UNITS)
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10
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2
4
6
8
10
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14
16
24
26
θ (COVERAGE IN MONOLAYER EQUIVALENTS)

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