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Infrared surface-wave interferometry on W(100)

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An IR grating on a clean W(100) surface is shown to generate both homogeneous and inhomogeneous surface electromagnetic waves. An observed interference between these two components, which can be described in terms of a two-beam interferometer with variable arm amplitude and fixed optical path, is used to measure the plasma frequency accurately in the IR.

The attenuation of surface electromagnetic waves (SEW's) propagating on a clean W(100) surface has been used to monitor adsorbate vibrational modes and changes in the free-carrier behavior of the metal in the room-temperature regime. We report on the measured properties of SEW's at elevated temperatures. At temperatures greater than 1000 K the SEW signal is attenuated to such a large extent that low-intensity surface skimming plane electromagnetic waves (PEW's), which are also generated at the grating coupler, can be detected. Since both kinds of wave are generated coherently at the input but travel across the surface with different velocities, interferometry is possible. This interferometer has been used to measure the plasma frequency of W in the 10-μm wavelength region.

A description of the experimental apparatus and procedures for making SEW attenuation measurements in ultrahigh-vacuum UHV conditions has been given in Ref. 2. Because the SEW wave vector is greater than that of light, gratings etched into the surface are used to couple CO2 laser radiation into and out of the SEW spectrum.

To identify the interference signature between SEW's and PEW's, the temperature dependence of the signal from the output coupler is measured at low temperatures agrees with that temperature dependence at a fixed frequency. Note the strong many laser frequencies across the ranges of the 12CO2 and 13CO2 laser gases. Each of the eight data traces shown in Fig. 1 represents an intensity-versus-temperature run at a fixed frequency, which is assumed to be a constant over the frequency region of interest. For a Drude metal in the 10-μm-wavelength region

\[ q_s \approx (\omega/c)[1 + \omega^2/2\omega_p^2 + (\delta_0 + 3\delta)(1 - 1/\omega^2)^2/2\omega_p^4], \]

where \( \omega_p \) is the plasma frequency in the IR and \( \delta_0 \) the low-frequency contribution to the dielectric constant from the interband transitions. Since the most effective PEW's are those within a wavelength of the surface at the output coupler, \( q_p = \omega/c \); hence the phase difference between the two arms for a Drude metal is

\[ \theta = (\omega L/c)(\omega^2/2\omega_p^2) + \phi. \]

The resultant intensity at the detector now takes on a familiar form, namely,

\[ I = I_S + I_P + 2(I_S I_P)^{1/2} \cos \theta. \]

Destructive interference occurs when \( \theta = (2n + 1)\pi \), with \( n \) a nonnegative integer, and the largest effect appears when the two arms of the optical bridge are balanced. A temperature sweep at a fixed laser frequency (the data shown in Fig. 1) corresponds to varying the relative amplitudes for the two components of Eq. (5) while keeping \( \theta \) fixed.

To obtain accurate values for \( \theta(\omega) \) each data set must be fitted to Eq. (5), so knowledge of the expected temperature and frequency dependences of \( I_S \) and \( I_P \) is required. The SEW intensity dependence is given in Eq. (1). Although an accurate expression for the PEW intensity dependence requires the solution of a deep grating diffraction problem, we show here that the appropriate temperature-dependent form can be constructed from a simple phenomenological model.

We assume that the near fields at the source that evolve into interfering PEW's and SEW's extend a distance \( \delta_0 \) above the grating and that the mean SEW amplitude height is a measure of this range. Now
consider a PEW traveling along the sample surface. In analogy with a parallel-plate transmission line geometry for fixed plate separation $\delta_0$, the transmitted intensity would be

$$I_p = I_0 p \exp(-2ry/\delta_0),$$

(6)

where $r$ is the normalized real part of the surface impedance of the metal and $y$ the distance along the surface.

Because of diffraction the height of the PEW actually changes with distance from the source; hence from the geometry

$$\delta(y) = \delta_0 + y \tan(\alpha),$$

(7)

where $\delta_0$ is the height at $y = 0$ and $\alpha = \sin^{-1}(\lambda/\delta_0)$, the angle to the first minimum in a single-slit diffraction pattern. The appropriate generalization of Eq. (6) is

$$I_p = I_0 p \exp\left(-\int dy[2r/\delta(y)]\right).$$

(8)

Another loss mechanism for this component occurs at the output coupler, $y = L$, since only the fraction $[\delta_0/\delta(L)]$ of the PEW will be coupled out to the detector. The resultant expression is

$$I_p = I_0 p (1 + fL/\delta_0)^{-1+2r/L},$$

(9)

where

$$f = \lambda(\delta_0^2 - \lambda^2)^{1/2}.$$ (10)

Three adjustable parameters $\theta$, $I_0 S$, and $I_0 p$ in Eqs. (1), (5), and (9) are used to fit the temperature-dependent data with the data near $I_S \approx I_p$ weighted most heavily. Figure 2 shows three data sets with the corresponding best fit given by this model. The destructive interference between the SEW's and the PEW's increases in strength as the laser frequency is decreased from 1072 cm$^{-1}$ [Fig. 2(a)] to 995 cm$^{-1}$ [Fig. 2(c)]. Sample movement produces the high-temperature difference between the data and the model shown in Figs. 3(b) and 3(c). The fits show that the PEW intensity at room temperature is $\approx 1\%$ of the SEW value. Even here the PEW component cannot be neglected since at frequencies where $\pi$ phase shift occurs the resultant intensity is $\approx 20\%$ smaller than for the SEW component alone.

In order to compare the results with relation (3) the measured phase angle $\theta$ is plotted against the frequency cubed as shown in Fig. 3. A linear dependence is observed over the measured range covering nearly $\pi$ rad. A least-squares fit to these data gives $L/(2\omega_p^2) = 1.04(\pm0.04) \times 10^{20} \text{ sec}^{-3}$ and $\phi = -0.51(\pm0.05)\pi$.

Our measurements show that the output coupling of both the SEW's and the PEW's takes place over the full extent of the 3.8-mm-wide output grating, so half of this distance is added to the separation between gratings to obtain the total propagation distance.
the first place) also leads to less than complete de-
vector (which causes the whole interference effect in
The second contribution comes from the difference in
the output coupler (and hence across all the detector).
tensities cannot be matched across the entire length of
destructive interference since the two components' in-
minimum. The first is that the SEW beam is attenu-
shown in 2(c).
There are two contributions to this 4% that temperature. [This is for the data at 995 cm-
measured value is -4% of the SEW (or PEW) value at
condition. At a frequency near 1000 cm-', where 0 =
the data points directly above them [since cos(π + x) = cos(π
- x)]. The solid line shows a linear least-squares fit.

Substitution of $L = 4.94$ cm gives $h\omega_p = 7.0(\pm 0.3)$ eV
for the plasma frequency in the IR.

By measuring the transmitted intensity as a function
of placement of the input beam on the input
grating, it has been possible to show that the PEW's occur not because of the impedance change at the
grating-smooth-metal boundary but instead because of
the finite number of grating lines intercepted by the
input beam (about 20 in the actual experiment). For a
plane wave incident upon an infinite grating at the
angle for maximum SEW generation the first-order
PEW beam is forbidden, but when the grating consists
of a small number of lines this selection rule against
the first-order beam is weakened, so some PEW's do appear. The end result is that a narrow grating coupler or a small spot size automatically sends PEW's along with the desired SEW's across the surface.

Another feature of our data that needs examination
is the finite intensity at the destructive interference
condition. At a frequency near 1000 cm$^{-1}$, where $\theta = \pi$, the resultant intensity should dip down to the back-
ground-noise level when $I_S = I_P$; however, the smallest
measured value is $\sim$4% of the SEW (or PEW) value at
that temperature. [This is for the data at 995 cm$^{-1}$
shown in 2(c).] There are two contributions to this 4% minimum. The first is that the SEW beam is attenuated more strongly than the PEW beam along the deep grating couplers. This leads to less than complete destructive interference since the two components' intensities cannot be matched across the entire length of the output coupler (and hence across all the detector). The second contribution comes from the difference in SEW and PEW wave vectors. This difference in wave vector (which causes the whole interference effect in the first place) also leads to less than complete de-
structive interference since the phase angle $\theta$ is not a constant across the whole output coupler. From measured values of the difference in attenuation and wave vector of the two components we calculate minimum $I/$

$I_S$ (or $I/I_P$) $\approx$ 2.5%, in reasonable agreement with the measured value of 4%.

The experimentally determined value of the con-
stant phase factor $\phi = -\pi/2$ cannot be explained within
the framework of this simple phenomenological pic-
ture. A rigorous diffraction calculation may be re-
quired for the relative phases of the two components
at the input and output coupler to be explored.

Our direct determination of the real part of the
inverse dielectric function of a clean W(100) surface
that we have characterized with an effective plasma
frequency ($h\omega_p = 7.0$ eV) in the Drude model approxi-
mation can be compared with the value deduced for
the same frequency region from reflectivity measurements ($h\omega_p = 6.4$ eV). The errors in these earlier measurements are large enough that
the two values are within the uncertainties.

This new measurement technique is not limited to
W. From relation (4) the criterion for destructive interference (assuming that $\phi = -\pi/2$) can be rewrit-
ten in terms of the SEW attenuation coefficient in Eq.
(1) to give

$$
\omega^2 L \rho(T)/4 \pi c = 3\pi/\omega t.
$$

(11)

Inspection of the right-hand side of this expression shows that the IR frequency should be chosen to en-
sure that $\omega t > 1$ for a particular metal so that the attenuation of the SEW will not obscure the interference effect.

The analysis given here, which uses the interference
between SEW's and PEW's to determine the plasma
frequency of the metal, should have general applica-
bility in the IR. Moreover, to produce such an effect
gratings are not required, since the interference has already been detected with an aperture-excitation technique on a smooth metal surface.

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