CONF-8708110--3

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Plasmon resonance absorption in layered structures of silver with periodic corrugation

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ABSTRACT

Plasmon resonance absorption in periodically corrugated layered structures of silver was studied by the photoacoustic method. The layered structures were self-supporting and corrugated with a period of 1888 nm and amplitude varying from 6 to 12 nm, depending on the thickness. Experimental results of resonance absorption of 633-nm photons were analyzed in terms of the propagation and damping constants of coupled modes of surface plasmons. The coupling efficiency of incident photons to these modes was found to be strongly dependent on corrugation amplitude and layer thickness.

1. INTRODUCTION

Resonant coupling of incident photons to surface plasmons in a periodically corrugated metal surface and subsequent interactions of surface plasmons with surface corrugation structure have been the subject of many recent investigations. Most of these works have dealt with a single corrugated surface on a semi-infinitely thick metal and, hence, with surface plasmons as a single-surface mode. It is well known theoretically that in a layered structure, surface plasmons on different interfaces interfere with one another and set up coupled modes, whose number, in general, is equal to the number of interfaces.¹ In this paper we report experimental results of plasmon resonance absorption due to excitation of coupled modes in a periodically corrugated single layer of silver (see Refs. 2 and 3). The results are analyzed in terms of the propagation and damping constants of the coupled modes and the coupling efficiency of incident photons to these modes as a function of layer thickness and corrugation amplitude.

2. EXPERIMENT

The self-supporting thin silver layers with periodic corrugation were made by evaporating silver onto a piece of plastic sheet grating which was overcoated with a thin collodion film. The silvered side of the grating was glued onto a 2x10-mm² aperture of an aluminum frame and then immersed into a pool of amylacetate. The collodion film dissolved away within a few hours, leaving a corrugated silver layer.

The spatial period d and amplitude h of corrugation of these layers were determined by measuring the first-order diffraction angle and intensity at normal incidence, respectively. The values of d were determined to be (1888 ± 3) nm. The values of h were found to vary from 5.7 to 11.9 nm with layer thickness varying from 26 to 121 nm. Absorption of 633-nm photons from a 1-mW He-Ne laser in these layers was measured by the photoacoustic method as a function of angle of photon incidence θ , details of which were described before.⁴ The measurements were made with p-polarized photons in the planar diffraction geometry.

3. EXPERIMENTAL RESULTS

Absorption as a function of θ for the 121-nm-thick layer exhibited sharp peaks at two different angles, 44.8° and 21.7°, due to plasmon resonances. (See Figure 1.) These peaks corresponded to the $m = +1$ and $+2$ resonances, respectively, given by the resonance condition $k = (\omega/c)\sin\theta + m(2\pi/d)$, where k is the surface plasmon wave number. These features of resonance absorption observed for a thick layer resulted from excitation of the single-surface mode.

The thinner layers exhibited resonance absorption in the same angular regions as exhibited by the 121-nm-thick layer. However, each peak was found to split into two peaks--one at a higher angle and the other at a lower angle. This splitting was due to excitation of coupled modes resulting from the interaction between surface plasmons on the two sides of the layers. The modes observed at the lower (the k^- mode) and the higher (the k^+ mode) resonance angle corresponded to the asymmetric and symmetric modes, respectively. The angular spread between these modes was found to increase as the layer thickness decreased.

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Figure 1. Photoacoustic signals from periodically corrugated, self-supporting thin silver films observed as a function of the angle of incidence of p-polarized 633-nm photon. Groove separation = 1888 nm.

Also, the resonance widths of the k^- and k^+ modes were found to become narrower and broader, respectively, with decrease of layer thickness, exhibiting their long- and short-range propagation properties. (See Figures 2 and 3.)

These results of the resonance angle and the resonance width as a function of layer thickness were compared with theoretical results of the propagation and damping constants, respectively, derived from the dispersion relation of coupled surface plasmons in a single layer system with no periodic corrugation.¹ It was found that agreement between the experimental and theoretical results was generally satisfactory. There were indications that the slight discrepancies found between them were due to microscopic imperfections and irregularities of the silver layers and not to the periodic corrugations.

The resonance absorption intensities were analyzed by integrating the area under the absorption peaks and taking into account the effect of thermal factors on the observed photoacoustic signal. It was found that the total intensities of the k^- and k^+ resonances depended linearly on h^2 , the square of the corrugation amplitude. However, this dependence was only approximate, indicating other effects. The total intensity for each layer was, therefore, normalized to a constant corrugation amplitude and plotted as a function of layer thickness. The results showed that the total intensity increased with increase of layer thickness and reached a maximum at layer thickness 90 nm, above which the coupled modes ceased to be excited and only the single-surface mode was excited on the incident side of the layer.

4. DISCUSSION

The thicknesses of the silver layers were of the order of the decay length of the plasmon field inside the layers. The corrugation amplitudes of these layers were also a significant fraction of the layer thickness and, hence, of the decay length of the plasmon field. Under such circumstances, it was of interest to explore the effects of periodic corrugation on the propagation and damping properties of coupled surface plasmons. However, the corrugation amplitudes in the range of the present silver layers were too small to yield a significant effect. This result has been confirmed theoretically by Gupta et al.⁵ who have made a non-perturbative calculation on periodically corrugated silver layers of the type used in the present study. As an extension of the present study, it is of interest to study plasmon resonance in periodically corrugated metallic multilayers by the present experimental technique. Such a study is now under way.

5. ACKNOWLEDGEMENTS

This research was sponsored by the Office of Health and Environmental Research, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Fig. 2. The propagation constants k_{SP} observed for the k^+ - and k^- -modes of coupled surface plasmons in periodically corrugated, self-supporting, thin silver films as a function of film thickness. The two solid curves represent the real part of the complex wave number $k (= k_1 + ik_2)$ for these modes in planar silver films calculated from their dispersion relations.

Fig. 3. The resonance half-width Δk observed for the k^+ - and k^- -modes of coupled surface plasmons in periodically corrugated, self-supporting, thin silver films as a function of film thickness. The two solid curves represent twice the imaginary part of the complex wave number $k (= k_1 + ik_2)$ for these modes in planar silver films calculated from their dispersion relations.

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