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Effect of Tantalum and MgO adhesion layers on plasmonic nanostructures

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ABSTRACT

Plasmonic structures have a wide variety of sensing applications because of their high field localization effect that leads to high sensitivity at lower powers. Specifically, plasmonic nanohole arrays are attractive platforms for sensing because of their easy alignment and measurement. In terms of fabricating these sensors, usually an adhesion layer is needed to ensure firm contact between the plasmonic metal layer and the substrate. Most fabrication efforts rely on titanium or chromium based metallic adhesion layers. However, the presence of the adhesion layer may hinder the plasmonic resonance by broadening the resonance and reducing the plasmonic field enhancement. This leads to degradation of sensing capabilities. We investigate the effect of tantalum, chromium, and titanium adhesion layers on plasmonic sensors made of nanohole arrays. Using the bulk refractive index data for metallic adhesion layers, we show that tantalum has the potential to show less damping effect compared to commonly used chromium and titanium. However, it still causes significant damping because of its high absorption, which becomes even larger for tantalum thin film according to our ellipsometry measurement results. We also propose here to use MgO dielectric adhesion layers to avoid the damping effect. Our investigation on MgO adhesion layers shows strong adhesion properties without scarifying sensor performance. Moreover, we will present an alternate sensor geometry that is less prone to damping by the adhesion layer and that can enhance the plasmonic resonance even if there is a metallic adhesion layer.

Keywords: Plasmonics, Nanohole arrays, Adhesion layer, Sensing

1. INTRODUCTION

Plasmonic nanostructures have lots of applications in sensing, including biosensing and chemical sensing. They provide high sensitivity because of strong field localization around the metal surface at their plasmonic resonance.[1–4] There is plenty of research on highly sensitive plasmonic nanostructures based on different shapes of nanoholes or nanoparticles. In specific, plasmonic nanohole arrays have attracted plenty of attention in sensing applications, since they are simple to align and measure in practice.[1,5] Also, a wide range of studies on plasmonic nanostructures has been devoted to plasmonic structures supporting highly sensitive Fano resonances resulting from coupling of a bright (superradiant) mode and a dark (subradiant) mode.[6–11]

In plasmonic sensing applications, the most commonly used metals are gold and silver, which are both noble metals. This means that they cannot adhere firmly to the commonly used dielectric substrates like Si or SiO_2. To create a strong adhesion, there is a need for using a very thin adhesion layer, typically with the thickness of 5 nm to 10 nm. The most common adhesion layers used in plasmonic sensors are Cr and Ti. However, they have high losses (large extinction coefficient), which results in damping of the nanostructure's plasmonic resonance and therefore causes resonance damping, showing up as resonance broadening and contrast reduction in the

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spectral response.[12–14] This puts a limit on sensing performance of the plasmonic nanostructure, reducing its figure of merit (FOM), defined as sensitivity divided by linewidth.[15]

Among the large number of research devoted to sensing aspect of plasmonic nanostructures, only a small portion focuses on the effect of adhesion layer on their plasmonic resonance. Previous studies show that both adhesion material properties and the overlap of adhesion layer with plasmonic hotspots play a role in severity of resonance damping and sensitivity degradation. It has also been shown that Cr and Ti adhesion layers result in significant plasmonic damping and broadening.[15–17] To avoid such plasmonic damping, dielectric adhesion layers or using a molecular linker are proposed in the literature.[16,18–21]

In the search for low-loss adhesion layers, here we study Ta and MgO as alternatives to the previously suggested metal and dielectric adhesion layers for plasmonic nanostructures. Ta was previously used as adhesion layer between a noble metal and a dielectric substrate.[22,23] However, there is no report on its thin-film material properties and how it affects the resonance in plasmonic nanostrucures. Also, to the best of our knowledge, MgO has not been used for adhering noble metals on dielectric substrates. In the following, designs of a nanohole array and a dimer nanohole array on a gold thin film on SiO_2 substrate are presented to show the effect of Ta and MgO adhesion layers on their plasmonic resonance, and to perform comparisons with typical metal and dielectric adhesion layers.

2. EFFECT OF Ta AND MgO ADHESION LAYERS ON PLASMONIC NANOSTRUCTURES

To study how Ta and MgO adhesion layers affect the optical behavior of plasmonic nanostructures, we first provide the simulation results for nanohole array, by considering the bulk material properties of adhesion layers in simulations. Furthermore, since thin-film material properties are different from bulk material, to get a practical insight on how a thin-film layer of Ta or MgO affects the plasmonic resonance, we performed ellipsometry measurements for thin-film layers of Ta and MgO with 5 nm thickness, and included the results in a second set of simulations.

After investigating the nanohole array structure, similar simulation results are provided for a dimer nanohole array structure, to show how different plasmonic structures can show different tolerance to the effect of adhesion layer on their optical properties. The results show that dimer nanohole array structure is less prone to damping by the adhesion layer.

2.1 Nanohole Array

To show the effect of MgO and Ta adhesion layers, simulations of a nanohole array are performed. The nanohole array is designed in a gold layer of 60 nm thickness, on SiO_2 substrate (n = 1.45). the cover material (top layer) is considered to be air for both cases. A unit cell of the designed nanohole array is shown in Fig. 1 (a). For the designed nanohole array, a period of 395 nm and a nanohole diameter of 180 nm are chosen, which supports a surface plasmon polariton (SPP) resonance at the gold / substrate interface around 710 nm wavelength, showing up as a transmission peak in its transmission spectra.

The simulated transmission spectra for the designed nanohole array, without adhesion layer and with different adhesion layer materials of 5 nm thickness are shown in Fig. 2. In the case of no adhesion layer, the substrate is assumed to be etched with a depth of 5 nm where the nanoholes are. Also, in all cases with adhesion layer, the adhesion layer is considered to be etched at the location of nanoholes. The results for transmission spectra are categorized in two separate plots, one considering the bulk material properties for adhesion layers (Fig. 2(a)), and the other one considering the thin-film material properties for adhesion layer materials (Fig. 2(b)). Fig. 2(a) shows how MgO and Ta compare to Ti and Cr, and Fig. 2(b) shows the estimated effect of Ta and MgO adhesion layers on plasmonic response in practice, since thin-film material properties are different from bulk material properties when fabricated. The thin-film material properties for Ta and MgO used for simulations of Fig. 2(b) are taken from our ellipsometry measurements performed on thin films of 5 nm. Also, simulation result for the case of ITO, as a typical dielectric adhesion layer to compare with, is obtained according to its thin-film material properties.[18]

The simulation results in Fig. 2(a) show that Ta causes larger plasmonic damping, meaning resonance broadening and contrast reduction, compared to commonly used adhesion layers, Cr and Ti. Also, from Fig. 2(b) compared to Fig. 2(a), one can observe that thin-film Ta causes even larger damping compared to the case where bulk material data were used for Ta in simulations. This is because Ta thin film has a larger extinction coefficient. Finally, MgO shows almost no effect on plasmonic response of the nanohole array, which makes it a good alternative to the metallic adhesion layers, and even to ITO, since it has lower losses.

2.2 Dimer Nanohole Array

As mentioned above, the effect of adhesion layer on plasmonic resonance, depends on the plasmonic nanostructure and the type of resonance. Therefore, we performed simulations similar to the case of nanohole array, for a dimer nanohole array structure.

A unit cell of the designed dimer nanohole array is shown in Fig. 1 (b). The period along the nanohole dimer axis is 695 nm, the period perpendicular to the nanohole dimer axis is 300 nm, the nanohole diameter is 200 nm, and the interhole spacing in a dimer nanohole unit cell is 100 nm. Again, a gold layer of 60 nm thickness, on SiO_2 substrate is considered. The dimer nanohole array shows a plamonic Fano resonance, resulted from coupling of an SPP mode (bright mode) and a Rayleigh-Wood anomaly (WA) mode (dark mode), at the gold / air interface. The Fano resonance for this design is around 710 nm, which appears as a dip in its transmission spectrum.

Similar to nanohole array, simulations of the desinged dimer nanohole array were performed without and with adhesion layer. Again, two categories, considering the bulk material data for adhesion layers (Fig. 3(a)), and considering thin-film material properties (Fig. 3(b)) are reported.

The results show similar trend of resonance damping caused by losses of Cr, Ti, and Ta, meaning that Ta causes the smallest plasmonic damping among the metal adhesion layers included, which is because of its smaller extinction coefficient. Also, one can observe that MgO has the least effect on the plasmonic resonance, and is a better choice compared to ITO, since it causes almost no reduction in resonance contrast. Finally, it can be seen that the resonance broadening and contrast reduction for lossy adhesion layers is less than in the case of the nanohole array discussed above. The reason is that the resonance for which the nanohole array is designed for provides a stronger field localization at the gold / substrate interface, where the adhesion layer is placed. This is not the case for the designed dimer nanohole array, which has a stronger field localization at the gold / air interface at its plasmonic Fano resonance. An example would be the case of thin-film Ta which causes a reduction of around 85 percent in resonance contrast for the nanohole array, while a contrast reduction of 45 percent is observed for dimer nanohole array with the same adhesion layer material properties.

3. SUMMARY AND CONCLUSION

The effect of Ta and MgO has been studied on two plasmonic nanostructures: nanohole array and dimer nanohole array. Comparisons with commonly used adhesion layer are made based on both bulk material properties and thin-film measurement data. The results show that Ta causes less plasmonic damping compared to the Cr and Ti, which are commonly used as adhesio layers. Also, MgO shows up as promising as a lossless adhesion layer, which causes almost no plasmonic damping.

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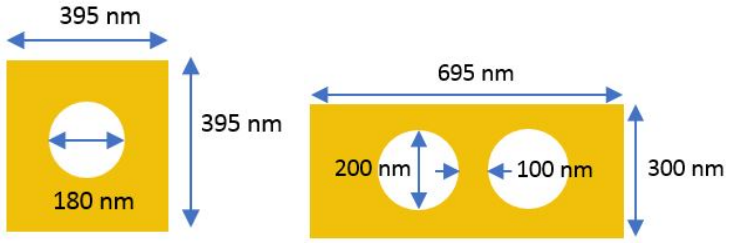
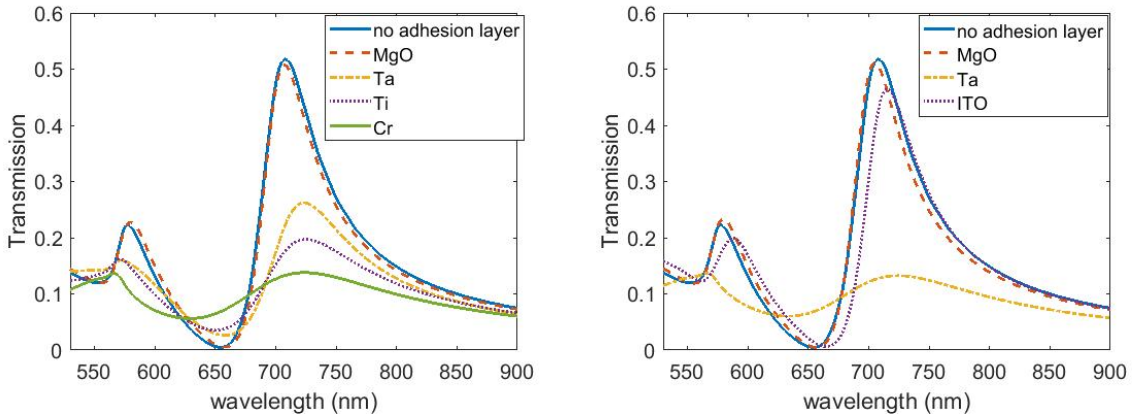


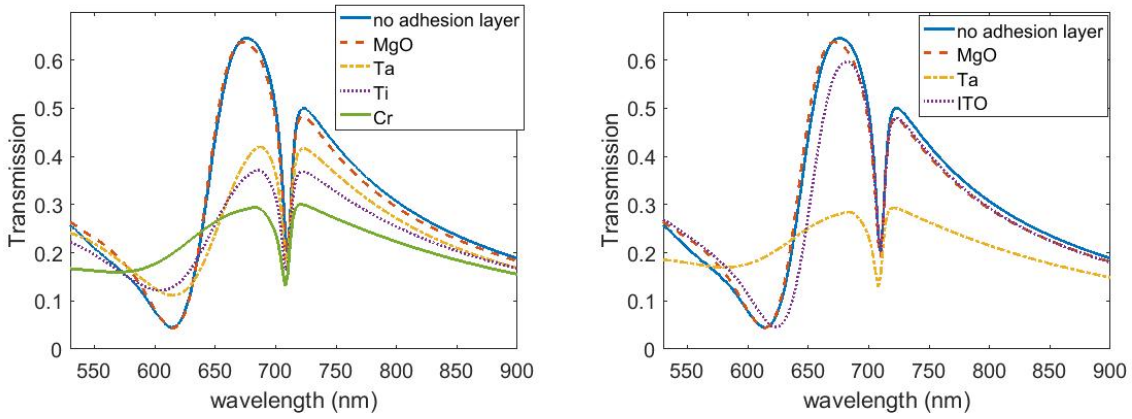
(a) (b)

Figure 1. Unit cell of the designed periodic nanostructures (a) nanohole array, (b) dimer nanohole array.



(a) (b)

Figure 2. Transmission spectra of the designed nanohole array without adhesion layer and with different adhesion layers (a) considering bulk material properties for adhesion layers (b) considering thin-film material properties for adhesion layers.



(a) (b)

Figure 3. Transmission spectra of the designed dimer nanohole array without adhesion layer and with different adhesion layers (a) considering bulk material properties for adhesion layers (b) considering thin-film material properties for adhesion layers.

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