# Surface roughness of Ag film on the optical properties of metal-dielectric-metal film and super-resolution imaging

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**Abstract**

In this paper, we will discuss the seed layer assisted smooth Ag film deposition and the effect of the surface roughness on the surface plasmon resonance in thin Ag film, the reflectance spectra of Ag/MF2/Ag structure and the super-resolution imaging by using a Ag superlens. Ni is found to be the effective surfactant in forming smooth Ag film and enhanced surface plasmon resonance. The Ag films deposited with and without seed layer were applied to the near field superlens application. High image contrast and sub-50nm resolution imaging were demonstrated. The effect of surface morphology on the optical properties in metal-dielectric-metal (MDM) thin film was investigated and an empirical relationship was found between the optical properties and the Ag film structural properties.

## 1. Introduction

Surface plasmon and metamaterials have attracted many attentions worldwide in the past decade for their interesting physics and many applications in such as super-resolution imaging, spacers, cloaking, ultra-compact light confinement. Silver is the most widely used plasmonic material for its low contact resistance, low refractive index, low damping loss and high reflectivity in visible range. However, thin silver film deposited by traditional methods exhibits a rather rough surface due to the Volmer-Weber mode growth and is undesirable for their significant surface plasmon polariton (SPP) scattering loss. The inhomogeneity of surface morphology would also sensitively influence surface plasmons at the metal-dielectric interface giving rise to performance degradation. Several methods have been developed to make smooth Ag film [1-3]. In this paper, we will give a brief overview of the Ni and Ge seed layer assisted smooth Ag layer deposition and their effect on the surface plasmon resonance (SPR), discuss about the results on high contrast superlens application, and the effect of surface roughness on the optical properties of the metal-dielectric-metal structures.

## 2. Results and Discussions

Ag films with a thickness of about 50nm had been deposited on Si and quartz substrate with and without a Ge or Ni seed layer by ebeam evaporation. It was proved that both Ni and Ge are effective in reducing the surface roughness of Ag film. The Ag/Ni films showed an improved rms surface roughness varying from 1.3 ~ 1.7 nm on both silicon and the Ag/Ge films showed a rms roughness of about 0.7 nm, comparing to a rms roughness of above 4 nm for Ag film without any seed layer. Figure 1 shows the correlation functions of surface roughness from the measured AFM data for the Ag, Ag/Ni and Ag/Ge film. The Ag/Ge film has the narrowest and lowest peak while the Ag film is on the opposite side. However, the SPR spectroscopy measurement and theoretical calculations have shown that the Ag/Ge film has the lowest figure of merit (FOM), which is proportional to the difference of reflectivity between the critical angle and resonance angle in SPR spectrum but inverse proportional to the

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reflectivity at the critical angle and the linewidth of the peak. It tells that even though a Ge seed layer can reduce the Ag film roughness, it unfortunately deteriorates the overall surface plasmon response due to the higher loss of Ge than Ag in the visible frequency range. On the other hand, Ag/Ni film exhibits larger FOM than Ag film in both the experimental data and the calculated result with roughness taking into account, which shows the promising of Ag/Ni in surface plasmon and metamaterials applications.

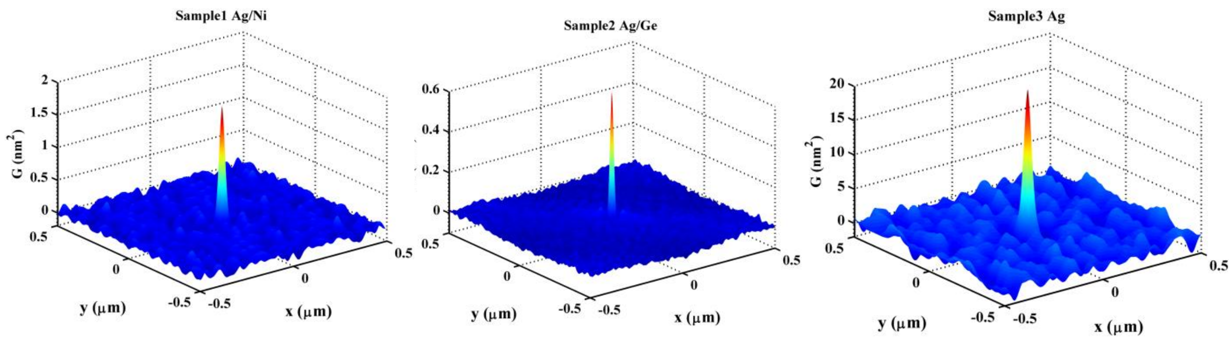
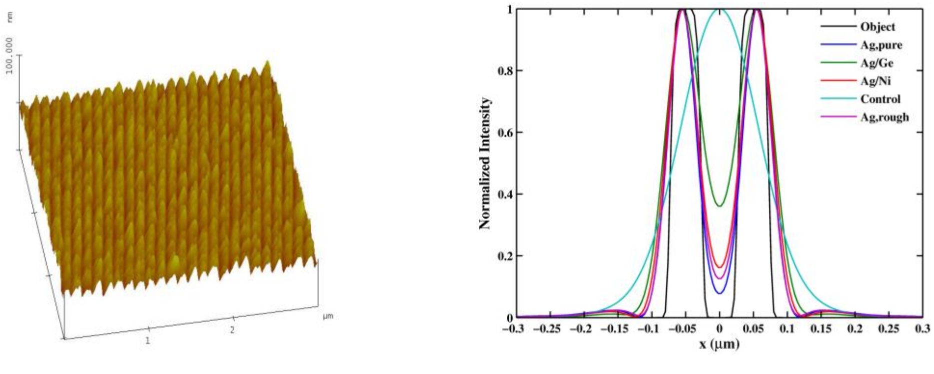



Fig. 1. The correlation plots for silver thin films show their smoothness. The narrower and lower the centre peak, the smoother the film.

Superlens by using a thin Ag film had been proved to be able to realize sub-diffraction limitation imaging at near field. Image contrast and resolution are the key factors to evaluate superlens imaging ability. The sub-diffraction-limited image has normally been converted into the photoresist (PR) topographic modulations and then read by AFM scanning. We applied the Ag, Ag/Ni and Ag/Ge film to the superlens application by using the a Cr grating with a linewidth of 55nm and space of 45nm as the object. A planarization process before the Ag film deposition was conducted and achieved a smoothness of less than 1nm. A typical depth of about 40nm was obtained by scanning over the surface topography of the developed PR in the pure Ag superlens, while it was about 25nm-30nm for Ag/Ni superlens, and below 20nm for Ag/Ge lens.




(a) (b)

Fig. 2. (a) Sub-diffraction-limited optical images by superlens scanned by AFM. (b) Point spread function calculation of the superlens imaging effect for different Ag layers.

Figure 2(a) shows a typical AFM image of the developed PR after the Ag superlens imaging process; 2(b) shows the simulated point spread function for different Ag layer superlens. Both experimental and simulation results showed that the Ag superlens has the highest contrast compared to Ag/Ni and Ag/Ge superlens. The key reason could be that all the Ag layers deposited on the smooth planarization polymer layer have no big difference in surface roughness and the role of seed layer in reducing surface roughness is not eminent in the superlens structure. The FWHM of the cross-section of the image PR line was measured at about 70nm.

The effect of surface morphology on the optical properties in metal-dielectric-metal (MDM) thin film was also investigated by using a Ag/MgF2/Ag system deposited on Si substrate with varied evaporation rate and thus different surface roughness and grain size. The reflectance spectra of the Ag/MgF2/Ag films show a dip due to surface roughness-induced excitation of surface plasmon polaritons. The dip position varies from 650 to 800 nm, depending on the surface morphology of the multi-layered film. Fig.3a shows the reflectance spectrum for samples at different deposition rate. The SPP excitation at the air/Ag interface due to the surface roughness is the main reason to cause the reflectance dip. The measured spectra are well matched with Fresnel reflection simulation of the multi-layer film by using the Drude-Lorentz function and Maxwell-Garnet theory for the discontinued Ag film. We found that the filling ratio of the Ag film plays an important role in determining the dip position while for the linewidth, the damping factor is the main contribution. Interesting empirical relations were also found between the optical properties and the morphology information, as showed in Fig. 3(b), where the dip position is proportional to filling factor f, surface roughness $\delta$ and the Ag grain size d, $\lambda \sim f\delta d3$.

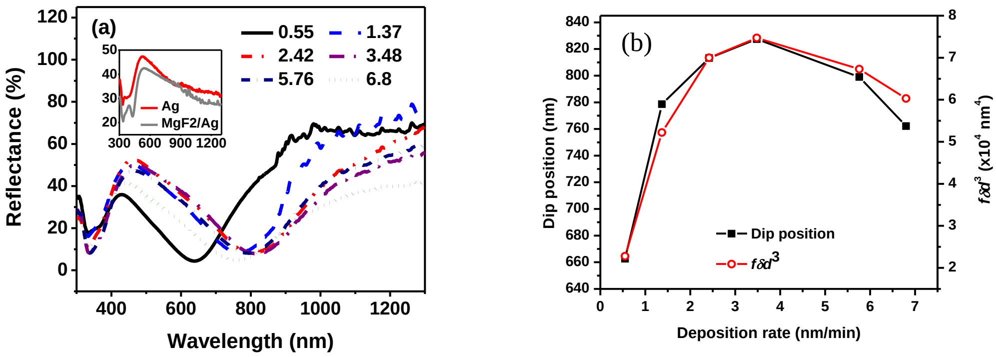



Fig. 3(a): Plot of different reflectance spectra for samples at different deposition rates. The inset shows the reflectance spectrum for a single Ag film and MgF2/Ag film on Si substrate. Fig. 3 (b): correlation between the dip positions of reflectance spectra with film morphology properties.

## 4. Conclusion

We discussed about the seed layer assisted smooth Ag film deposition and the effect on surface plasmon resonance. High contrast superlens using a flat Ag layer with a resolution of $\lambda/8$ were demonstrated and showed that smooth Ag film deposited on smooth planarization polymer layer without any damping effect from the seed layer has the highest contrast. The effect of surface morphology on a metal-dielectric-metal film was also studied and had the optical properties correlated to the surface roughness, filling factor and the grain size.

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