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Research Paper

Fabrication of Ultra-smooth 10 nm Silver Films without Wetting Layer

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Abstract Using conventional deposition techniques, we demonstrate a method to fabricate ultra-smooth 10 nm silver films without using a wetting layer or co-depositing another material. The argon working pressure plays a crucial role in achieving an excellent surface flatness for silver films deposited by DC magnetron sputtering on an InP substrate. The formation of ultra-smooth silver thin films is very sensitive to the argon pressure. At the optimum deposition condition, a uniform silver film with an rms surface roughness of 0.81 nm has been achieved.

Keywords: Silver, Ultra-thin, Surface roughness, Sputtering, Atomic force microscopy, Nanophotonics.

I. Introduction

Silver (Ag) is the most frequently used metal for metamaterial structures, surface plasmonic nanodevices, low-loss coatings, super lenses, micro cavities, and many other applications in the field of nanophotonics [1 – 7]. Silver has advantages over other metals in terms of its intrinsic properties, such as its low refractive index and low damping, which allow low loss and high reflectivity to be achieved in broad bandwidth covering both the visible and infrared regions [8, 9]. Ultra-thin Ag films deposited by electron beam evaporation, sputtering, electro-less plating, and chemical vapor deposition tend to have large grain sizes, and high surface roughness due to 3D island–like growth (Volmer-Weber growth mode), which severely degrades device performance in applications [10-15]. Properties such as surface roughness, thickness uniformity, and on-resonance or broadband optical efficiency are very important for thin films to achieve high performance.

For surface plasmonic or metamaterial applications, it is necessary to fabricate an ultra-smooth Ag thin film with sub-nanometer scale roughness and a high degree of thickness uniformity. In recent years, several approaches have been introduced to fabricate ultra-smooth, ultrathin Ag films using the influence of a wetting layer or the co-deposition of aluminum [16-21]. With the help of a wetting layer, Ag thin films of root mean square (rms) surface roughness of <1 nm (Ge, Cu) or ~1.3 nm (Ni) have been achieved [14,16,18]. In another approach, a small amount of aluminum is co-sputtered along with Ag, resulting in an excellent surface roughness of <1 nm [19]. Such a wetting layer or co-sputtering are likely to deteriorate device efficiency due to refractive index differences between them or high loss of the co-sputtered metal. Therefore, it is necessary to avoid the use of a wetting layer or co-doping in the fabrication of ultra-thin and ultra-smooth Ag films.

In this work, we report the fabrication of 10 nm ultra-smooth Ag films using a conventional sputtering deposition technique at room temperature. Film can be easily fabricated without the influence of a wetting layer, and without annealing or co-deposition, but only by adjusting the argon (Ar) working pressure. The thickness and the surface roughness of these ultrathin Ag films are measured by atomic force microscopy (AFM). Confirmation of the formation of ultra-thin films is verified by scanning electron microscopy (SEM).

II. Experiments and Discussion

The details of this work are divided into two parts. In the first part, we introduce the photolithography process with which an InP substrate is patterned using an AZ5214 positive resist. This process is used to determine the thickness of the ultra-thin Ag films after sputtering. In the second part, fabrication of ultra-smooth 10 nm Ag films by DC magnetron sputtering will be described, followed by AFM and SEM analyses.

1. Pattern creation by photolithography

An InP substrate with an rms surface roughness of 0.36 nm was chosen and cleaned with acetone, methanol, and iso-propyl alcohol. Fig. 1(a) outlines the pattern formation and silver deposition processes. The cleaned InP substrate was spin-coated with a positive resist, AZ5214. After the photolithography process, patterns were developed using AZ500. Silver was then sputter-deposited on the InP substrate at room temperature. Lift-off processing was

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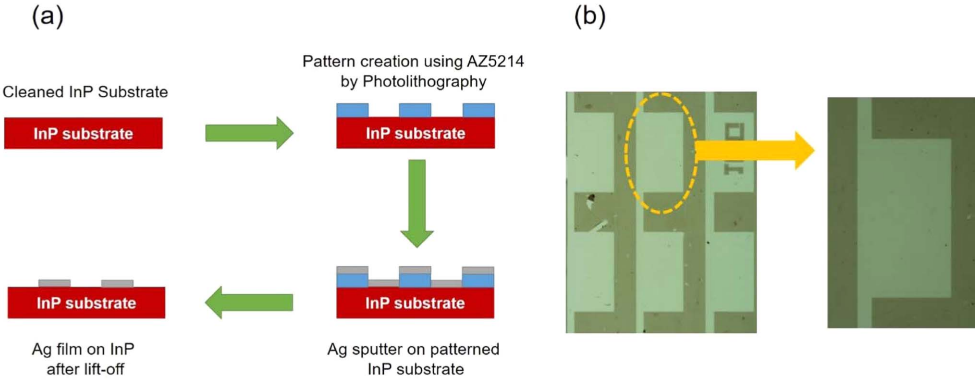

Figure 1. (a) Process of making positive resist patterns on InP substrate by photolithography and Ag sputtering, (b) Image of silver film deposited on InP substrate after lift-off process.

carried out to leave only silver patterns in the substrate. Fig. 1(b) shows a microscope image of a silver film on the InP substrate after the lift-off process for determining the thickness of the deposited film.

2. Fabrication of 10 nm Ag film by DC magnetron sputtering and surface topography analysis

An A320-XP UHV sputtering gun source (AJA International Inc.) was employed in the sputtering chamber. A 2-inch diameter Ag sputtering target with 99.99% purity was used. The patterned InP substrate was then loaded into the chamber, which was pumped down for 6 hours to reach a vacuum level of $\sim 3\times10^{-7}$ torr. During the deposition, the DC power supply was set at 40 W and Ar gas flow was set at 50 sccm, while Ar working pressure was varied to find the optimal deposition condition. The whole set of processes was carried out at room temperature.

Fig. 2(a) shows the importance of the Ar working pressure in achieving a smooth 10 nm Ag film. The Ar working pressure window is very narrow for successful formation of ultra-smooth 10 nm Ag films. At 45 mtorr Ar working pressure, we achieved a 0.85 nm rms surface roughness, which is comparable to the best results reported when using a wetting layer or co-sputtering. It is notable that significant roughness deterioration was evident even with ±5 mtorr differences from the optimal Ar working pressure condition. For the optimal deposition condition (45 mtorr Ar working pressure), the 10 nm ultra-smooth Ag film was deposited at a rate of 0.0067 nm/s. The thickness of the deposited ultra-thin Ag film was confirmed through the AFM line profile (Fig. 2c), which was obtained from a three dimensional AFM image (Fig. 2b).

The surface morphologies were characterized by AFM in non-contact mode. The observed area was 5*5 μm^2; three dimensional surface morphology images are shown in Fig. 3. Worse surface roughness can be clearly seen at the Ar working pressures of 35 mtorr (Fig. 3a), 40 mtorr (Fig. 3b), and 60 mtorr (Fig. 3d). At the optimal Ar working pressure, 45 mtorr, island-like growth is no longer observable and the formation of a thin film with ultra-smooth surface roughness of ~0.8 nm can be clearly seen.

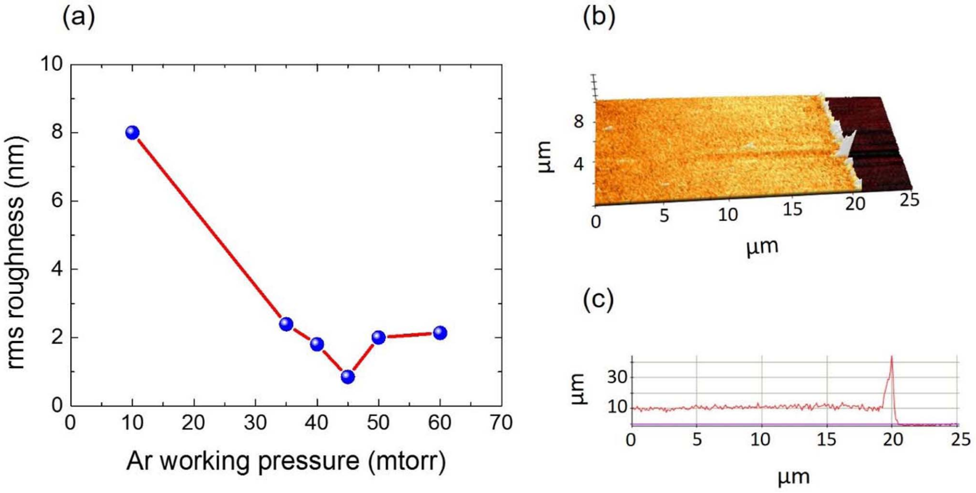

Figure 2. (a) Surface roughness trend of 10 nm Ag thin films as a function of Ar working pressure, (b) Portion of three dimensional AFM image of the deposited Ag thin film after lift-off process, (c) AFM line profile confirming the 10 nm Ag film thickness.

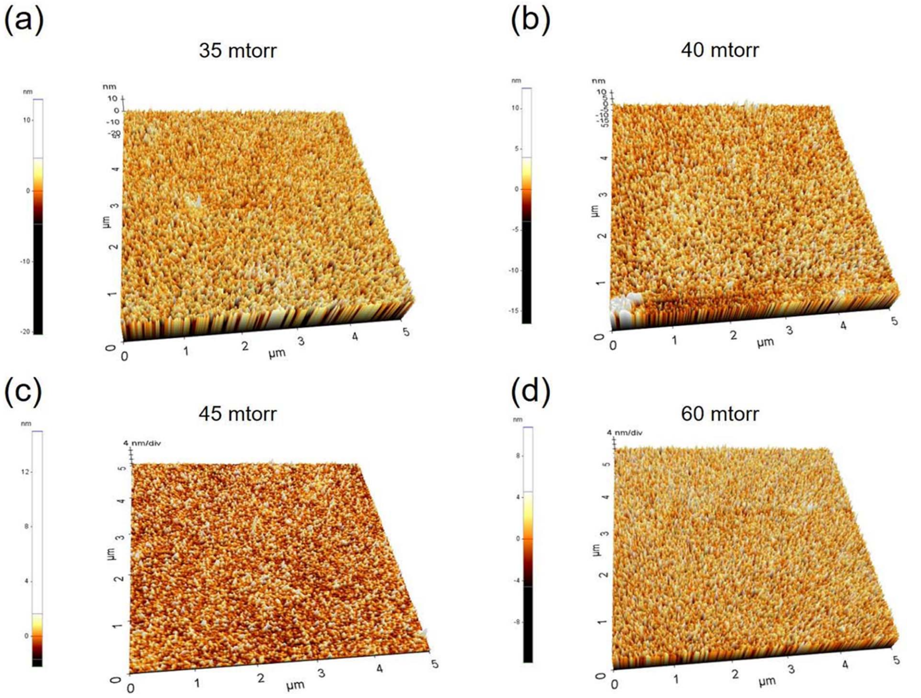

Figure 3. Three dimensional surface morphology images, measured by AFM, for the 10 nm Ag films deposited under Ar working pressures of (a) 35 mtorr, (b) 40 mtorr, (c) 45 mtorr, and (d) 60 mtorr.

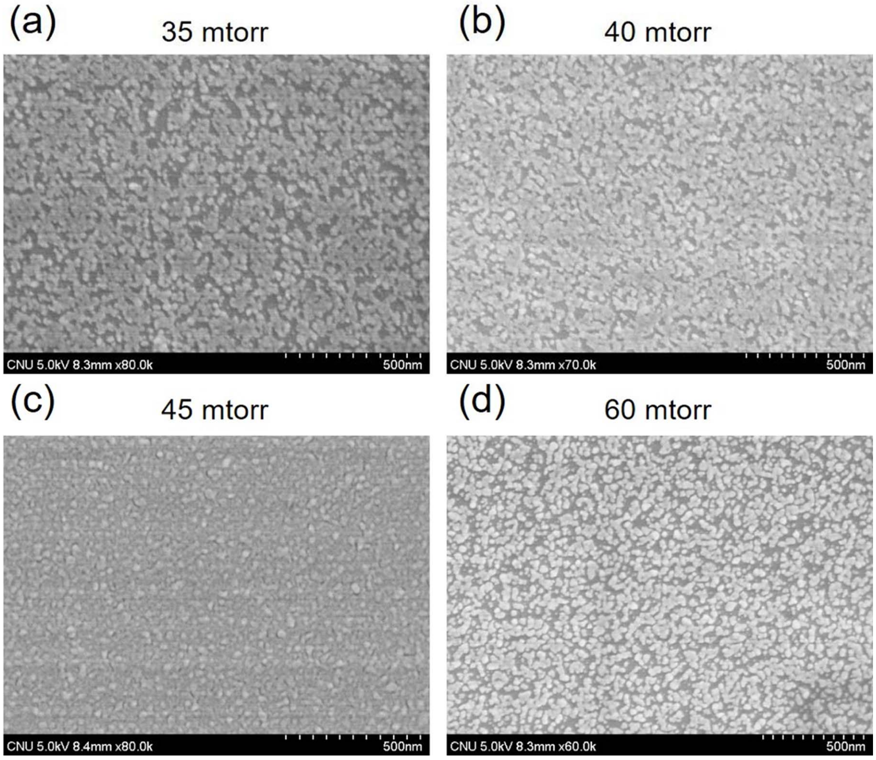

Figure 4. SEM images of the deposited 10 nm Ag thin film under Ar working pressures of (a) 35 mtorr, (b) 40 mtorr, (c) 45 mtorr, and (d) 60 mtorr.

This means that a very precise Ar working pressure is required for the formation of an ultra-smooth 10 nm Ag film and elimination of the Volmer-Weber growth mode. A high deposition rate occurs at low Ar working pressure conditions, resulting in the formation of islands and concomitant bad surface roughness. At high Ar working pressures, the number of Ar ions increases causing surface damage that degrades the surface roughness. At the optimal Ar working pressure, the above mentioned problems are solved, and the result is the formation of an ultra-smooth film [22]. The data are further supported by SEM images, provided in Fig. 4. Film formation at 45

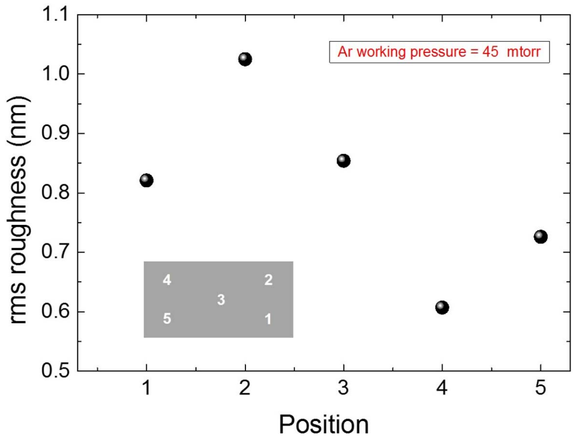

Figure 5. Confirmation of uniform surface throughout the 10 nm Ag deposited on InP substrate. The inset provides AFM scans of the positions. The size of the InP substrate is 10 × 5 mm^2.

mtorr Ar working pressure is clearly observable, whereas the formation of islands is visualized as resulting from the high surface roughness at other conditions.

To confirm the thickness uniformity of the sample, we deposited a 10 nm Ag film on another InP substrate and carried out AFM analysis of the sample. The surface roughness results were similar over the entire sample; surface roughness results from 5 representative positions are shown in Fig. 5. An average rms roughness of 0.81 nm was obtained throughout the sample, confirming the formation of a uniform 10 nm Ag film.

III. Summary

In summary, a 10 nm ultra-smooth Ag film was successfully fabricated using DC magnetron sputtering under room temperature condition. Surface roughness of 0.81 nm was achieved without using a wetting layer or co-deposition, but rather by optimizing the Ar working pressure in precise steps. The Ar working pressure has a very narrow optimum window and is critical in the formation of the ultra-smooth 10 nm Ag film.

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