Ultrathin, Smooth, and Stable Doped Silver Films

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Abstract:

Silver's low resistivity, high conductivity, and low loss in the visible and near-infrared (NIR) regions makes it perfect for many optoelectronic applications. However, pure silver deposited on a dielectric substrate is unstable, rough, and requires a thick layer to form a continuous film. Aluminum (Al)-doped silver has been shown to circumvent these issues and provide an ultrathin and low loss film with sub-nanometer roughness. This makes Al-doped silver (Ag) a viable alternative to indium tin oxide (ITO) as a flexible transparent conductor. With the benefits of Al-doped Ag known, the purpose of this project was to co-sputter other metals with Ag and observe the results. The roughness, resistivity, and optical properties of these different doped Ag films were measured and a comparison study was performed to compare their properties to that of Al-doped Ag.

Materials

Introduction:

Low loss in the visible and NIR regions makes Ag advantageous for use in many optoelectronic and metamaterial applications. However, the Volmer Weber growth of Ag on dielectric substrates and instability at room temperature results in a rough surface [1]. This significantly reduces Ag's use in many devices and makes it difficult to achieve an ultrathin and smooth film.

To circumvent these issues, a 1-2 nm germanium (Ge) seeding layer can be used resulting in Ag films with a smooth surface [1]. However, seeding layers are undesirable for low loss optical applications. This is especially true for Ge, because it is a low band gap semiconductor. Other methods to achieve stable and smooth Ag thin films have been proposed, but are either too optically lossy or too expensive and time consuming.

A way to create ultrathin, smooth, and stable Ag films with minimal time and cost has been shown by using Al in a co-deposition process with Ag. Al is co-sputtered along with Ag and this reduces the percolation threshold to 6 nm with an RMS roughness less than 1 nm for a 15 nm thick Al-doped Ag film [2]. This is a significant reduction from a pure 15 nm thick Ag film, which has a percolation threshold of 10-20 nm and an RMS roughness of about 6 nm [2].

With the knowledge that Al-doped Ag results in an ultrathin, smooth, and stable thin film, we created titanium (Ti)-doped Ag and chromium (Cr)-doped Ag films and investigated their properties. In this work, we compare the properties of the Ti- and Cr-doped Ag films to Al-doped Ag films.

Theory:

Metals, such as Al, affect the nucleation growth of Ag on dielectric substrates such as silicon dioxide (SiO_2). When Al and Ag are co-sputtered together, the strong bond Al has with oxygen from SiO_2 forms a high density of

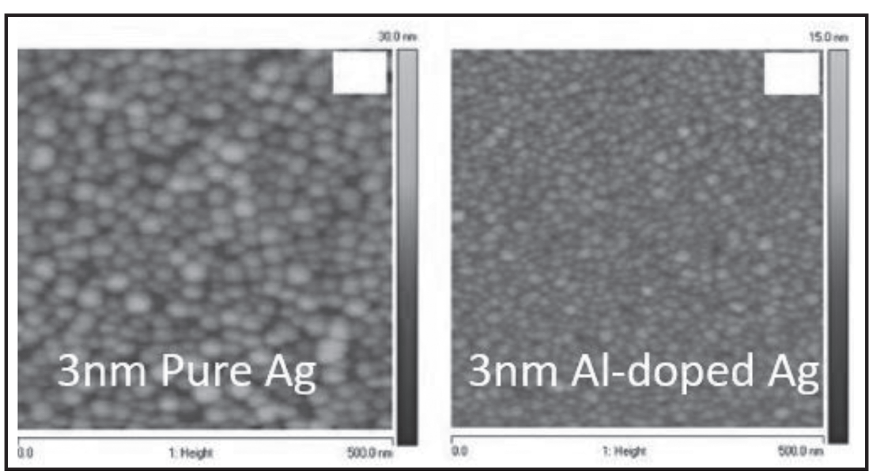

Figure 1: Nucleation sites.

nucleation sites on the surface of the SiO_2 substrate [1]. This acts as a seeding layer from which Ag can easily grow. This enhanced density of nucleation sites has been viewed from a 3 nm thick layer of Ag and Al-doped Ag deposited on SiO_2 as seen in Figure 1.

It is clearly seen that Al-doped Ag has a significantly larger number of nucleation sites compared to Ag deposition.

Along with an enhanced nucleation layer another benefit of co-sputtering with a metal is the formation of a capping layer. After deposition, when the sample is brought out into an oxygen ambient, there is a sudden in-diffusion of O_2 and an out-diffusion of Al, which results in a capping layer [1]. The benefit of a capping layer is that it prevents de-wetting, the agglomeration of Ag, and stabilizes the thin film. It is this combination of an enhanced nucleation layer and a capping layer that results in an ultrathin, smooth, and stable film.

Experimental Procedure:

Samples were made using diced <100> Si and fused silica resulting in 1 cm × 1 cm substrates to deposit on. Using a Kurt J Lesker Lab18 sputtering tool, recipes were created to perform Ti-Ag and Cr-Ag co-sputtering, resulting in Ti-doped Ag and Cr-doped Ag films. During deposition, the Ag target power was kept at a fixed value, while the Ti and Cr targets were varied from a low to high power. The purpose of this was to find the optimal power value to run the Ti and Cr targets that resulted in the least amount of optical loss from the thin film sample. After deposition, thickness and optical measurement were performed using the J.A Woollam ellipsometer. An atomic force microscope (AFM) was then used to provide surface roughness measurements while an SEM was used to observe film grain and continuity.

Results and Discussion:

The results from the Ti-doped Ag and Cr-doped Ag films showed that both metals did promote the growth of thin silver films just like Al. However, both films were inferior to Al-doped Ag films during initial testing.

The 9 nm thick Ti-doped Ag film resulted in an RMS surface roughness of 0.549 nm, with a sheet resistance of 51 Ω/sq, while the 9 nm thick Cr-doped Ag film was 0.709 nm and 25 Ω/sq, respectively. Comparatively, a 9 nm thick Al-doped Ag film has an RMS surface roughness of 0.6 nm with a sheet resistance of 24 Ω/sq.

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