Titanium nitride as plasmonic material for visible wavelengths

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Abstract

Transition metal nitrides such as titanium nitride show metallic properties at optical frequencies. We report that these materials can be better alternatives to conventional plasmonic materials such as gold and silver for metamaterial applications in the visible range.

1. Introduction

Metamaterials (MMs) have provided a new dimension to the scope and applications of nano-optics [1-3]. However, there are many practical difficulties associated with realization of MM-based devices that hinder their application horizon. One of the major problems in the optical range is the loss associated with the plasmonic constituents of MMs [4,5]. The losses in the conventional plasmonic components such as gold and silver are so high at optical frequencies that it is a grand challenge to compensate MM losses by any existing gain media [4]. Another critical factor is that real part of dielectric permittivity in conventional metals is too large in magnitude to be readily suitable for many MM designs. Thus, alternative plasmonic materials are essential for MMs operating in the optical range [5,6].

In the search for better plasmonic materials, transparent conducting oxides (TCOs) were proposed as low loss alternatives to gold and silver in the near-infrared [5]. However, TCOs cannot be plasmonic at visible wavelengths because their carrier concentration is limited to around $10^{21}cm^{-3}$ [7]. In this paper, we show that titanium nitride could be a good candidate for an alternative plasmonic material at visible wavelengths. We briefly describe the processing details and optimizations involved in the deposition of titanium nitride films and assess the performance of an important class of MMs, hyperbolic MMs based on titanium nitride.

2. Experiment

Titanium nitride is a ceramic material whose optical properties depend significantly on the preparation method. Titanium nitride can possess metallic properties at visible wavelengths because of large free carrier concentration (~ 10^{22} cm^{-3}) [8,9]. Interband losses are not completely absent in the visible spectrum. However, TiN exhibits smaller interband losses in the red part of the visible spectrum and a small negative real permittivity [9]. This makes titanium nitride a promising material for plasmonic metamaterial applications in the visible spectrum.

Thin films of titanium nitride were deposited on c-sapphire substrates by DC reactive magnetron sputtering (PVD Products Inc.) of a 99.995% titanium target in an argon-nitrogen environment. The films were deposited at a pressure of 5 mTorr with the flow of argon and nitrogen held at 4 sccm and 6 sccm respectively. The sputtering power was held constant for all depositions at 200 W (DC) and the target-substrate distance was 8 cm. About 150 nm thick films were deposited on c-sapphire. The substrate

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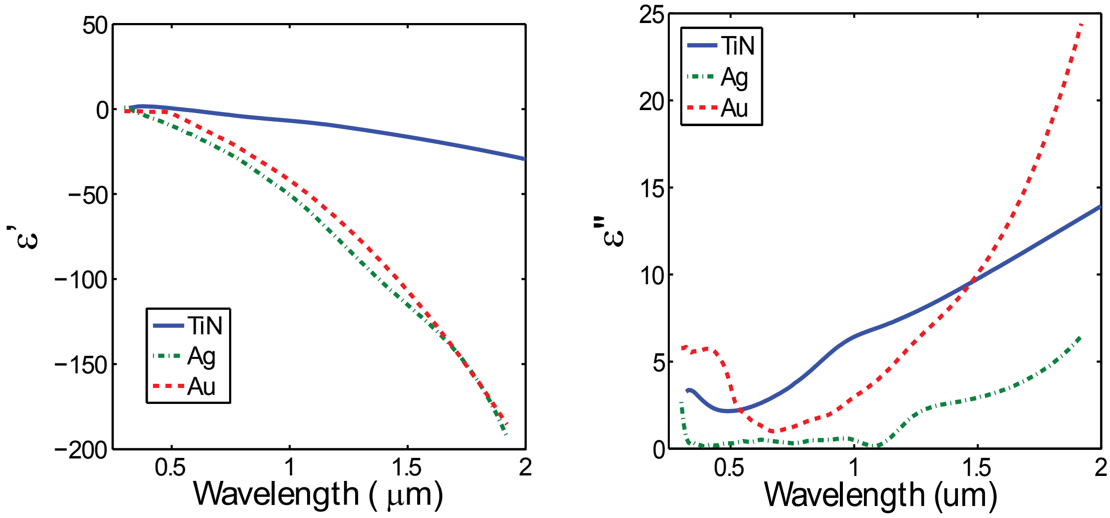

Fig. 1: Optical properties of titanium nitride film deposited by DC magnetron reactive sputtering. The dielectric function of TiN was extracted from spectroscopic ellipsometry measurements using Drude-Lorentz model. The optical constants of gold ans silver are from [10].

temperature during deposition was held at 500 ^{o}C. The resulting films were characterized by a variable angle spectroscopic ellipsometer in the near-IR, visible and near-UV wavelength ranges. A Drude-Lorentz (with 3 Lorentz oscillators) model provided good fit to the ellipsometric measurements. Fig. 1 shows the dielectric function retrieved for TiN films deposited at 300 ^{o}C as compared with silver and gold. The losses in TiN are lower than those in gold for long wavelengths in the near-infrared. Also, the real permittivity of TiN is much smaller in its magnitude than those of gold and silver in the visible spectrum making it suitable for MM-devices.

3. Hyperbolic metamaterials with TiN

Hyperbolic MMs (HMMs) are an important class of MMs exhibiting hyperbolic dispersion that enable applications such as sub-wavelength imaging and single photon gun [11,12]. HMMs can be realized by stacking alternating sub-wavelength thick layers of metal and dielectric [7,11,12]. The figure-of-merit (FoM) of such a HMM can be adopted as $Re\{\beta_\perp\}/Im\{\beta_\perp\}$ where $\beta_\perp$ is the propagation constant perpendicular to the plane of the layers [13]. The FoM of HMMs in the visible wavelengths formed by conventional metals and TiN is compared in Fig. 2. It is clear that TiN based HMM outperform conventional metal-based systems significantly. Thus, TiN is an alternative plasmonic material that enables efficient realization of MM-based devices in the visible spectral range.

4. Conclusion

We show that titanium nitride can serve as a plasmonic material for metamaterial applications at the visible frequencies. From the comparative study of the performance of hyperbolic metamaterials, devices with titanium nitride used as plasmonic constituent materail significantly outperform their metal-based counterparts.

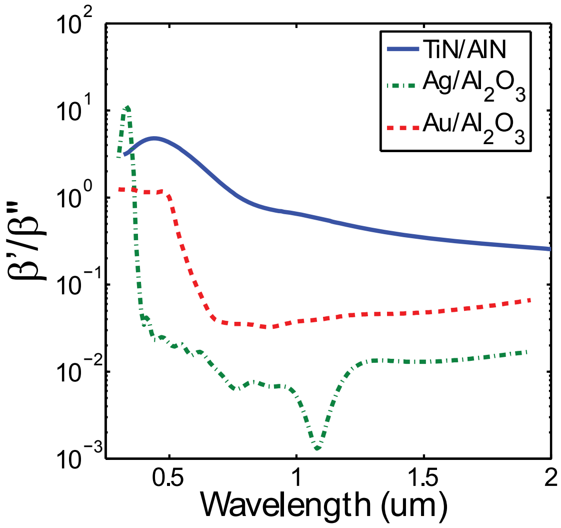

Fig. 2.: Figure-of-Merit of hyperbolic metamaterials (adopted from [9]) formed by layered stack of alternating sub-wavelength layers of metal and dielectric.

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