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Advanced Fabrication of Hyperbolic Metamaterials

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Abstract. Hyperbolic metamaterials can provide unprecedented properties in accommodation of high-k (high wave vector) waves and enhancement of the optical density of states. To reach such performance the metamaterials have to be fabricated with as small imperfections as possible. Here we report on our advances in two approaches in fabrication of optical metamaterials. We deposit ultrathin ultrasmooth gold layers with the assistance of organic material (APTMS) adhesion layer. The technology supports the stacking of such layers in a multiperiod construction with alumina spacers between gold films, which is expected to exhibit hyperbolic properties in the visible range. As the second approach we apply the atomic layer deposition technique to arrange vertical alignment of layers or pillars of heavily doped ZnO or TiN, which enables us to produce hyperbolic metamaterials for the near- and mid-infrared ranges.

FABRICATION OF HYPERBOLIC METAMATERIALS

Typically hyperbolic metamaterials are presented by a layered multi-periodic media or by a bundle of nanopillars or nanowires [1,2]. The alteration of conducting (for example, metals, transparent conducting oxides or heavily doped semiconductors) and dielectric (air, oxides or high-resistive semiconductors below the bandgap) insertions should obey the principle condition for the homogenization legitimacy – it must happen on scales much smaller than the operating wavelength. Therefore, optical metamaterials, and hyperbolic metamaterials in particular, require extremely small thicknesses of the layers (down to 10 nm and even below) or lattice periods and diameters of the wires/pillars. Needless to say, that fabrication of the unitary elements must be accompanied with a very low roughness of the surfaces.

Ultrathin Gold Layers

Gold is considered to be a backbone of plasmonics due to it conformal deposition, low material losses, inert behavior towards most of substances and open-air stability. So deposition of nanometers-thick gold films can be performed by sputtering techniques [3, 4] after a special preprocessing of the working surface with layers improving

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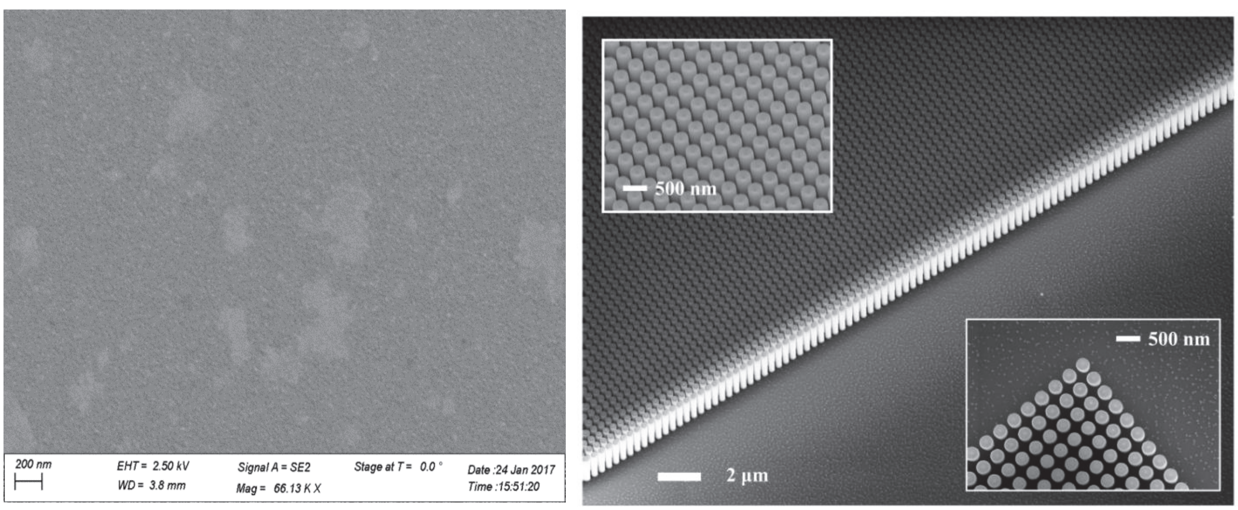
adhesion of gold to the substrate. Conventionally the Ti or Cr adhesion layers are in use. However, when the thicknesses of the film become very small, the properties of the adhesion layer can deteriorate the overall performance of the structure towards, e.g. surface or bulk plasmon-polariton propagation or localized surface plasmons Q-factors [5].

We proposed to use 3-Aminopropyl-trimethoxy-silane (APTMS) as an adhesion layer for gold, obtaining an ultra-thin, ultra-smooth gold film of the thickness of 6 nm and roughness below 0.30 nm [3]. We prove the superior quality of the layers deposited by our approach (Fig.1a) by detection of excitation of short-range surface plasmon polaritons. As a reference we use layers deposited with the Cr-adhesion or without any adhesion layer. As a next step in advancing technology we report on stacking of few periods of gold-dielectric bi-layers to deliver a high-quality hyperbolic metamaterial prototype.

Metamaterials with Vertically Arranged Elements

Another principal geometry that supports hyperbolic behavior is the so-called wire medium, e.g. an anisotropic composite of metallic pillars incorporated in a dielectric host matrix. Its one-dimensional analogue – trenched structure – can also exhibit specific hyperbolic dispersion of surface waves. Unfortunately, sputtering of gold cannot be used in fabrication neither of vertically standing nanopillars, nor vertical layers when even a moderate aspect ratio of unitary elements is required. The processing of such metamaterials can be done by atomic layer deposition (ALD), but gold then must be substituted by alternative plasmonic materials, which allow ALD processing, for example, aluminum doped ZnO [6,7].

We report on fabrication of extended arrays of AZO nanotrenches and nanopillars, which can be considered as metamaterials, in particular, hyperbolic metamaterials in mid-IR. Such choice is regulated by the period size, which is 400-500 nm due to limitations of the deep-UV laser lithography (Fig.1b).



(a) (b)

FIGURE 1. (a) 8 nm thick gold film deposited on APTMS adhesion layer; (b) Figure shows the bird-eye SEM image of finally prepared pillars, the insets shows the magnified image of pillars (top left) and top view of the array corner (bottom left).

Rather surprisingly, the tensor of the effective permittivity restored from the mid-IR reflectance spectra has a very strong anisotropy, but is positively defined. This astonishing discrepancy implies that AZO, once being confined in the nanopillar dimensions, becomes poor plasmonic material, and its permittivity significantly deviated from that of the flat film. So, this challenging fact poses a question of applicability of ALD deposited materials for hyperbolic metamaterials and definitely requires further attention.

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