AFM lithography for Tamm plasmons observation

A Shagurina, S Kutrovskaya, I Skryabin, A Kel’
Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky Street, Vladimir 600000, Russia

E-mail: 1lstella@mail.ru

Abstract The results of the formation of planar nanostructures with relief, repeating the trajectory of movement of an AFM probe were presented. The parameters affecting their geometric dimensions: height, width, uniformity in the layer, etc. were investigated. The method of induced deposition of silver/golden clusters on the silicon wafer surface p-type in the presence of an external electric field was developed. The possibility of using such structures as hybrid circuits using photoelectronic transducers was discussed.

1. Introduction
Noble metals nanostructures such as silver and golden nanoparticles are well known due to their ability of supporting surface plasmon localization at optical frequencies [1-2]. Such optical nonlinear gain effects are widely used in nanoparticle biological and chemical sensing, surface enhanced Raman scattering or in photoelectric applications. Their spectral response strongly depends on the nature of the metal, the size, the shape and the spatial arrangement of nanoparticles. The precise control of these parameters during fabrication process is the main goal for adjusting the optical properties of such structures in many applications [3].

Among the amount of different notable phenomena appeared in plasmonic structures the effect of the directional propagation of light observed in the silicon-metal interfaces deserves special attention. Such structures could potentially find a promising applications in all-optical information processing devices since it can transmit optical signals. A great number of various methods of fabrication of nanostructures supporting for plasmon resonances on metal-silicon interfaces were recently proposed. Most of them are based on complicated multi-step lithography methods which can be combined by perfec with different chemical etching techniques, electron beam evaporation and so on. All this procedures demand rather expansive equipment and well optimized technology. In this paper we propose an alternative easy and relatively cheap method of fabrication of metal nanostructures grown on a silicon substrate. The main peculiarity of the proposed technique is the ability to control the shape and morphology of the designed structure. The proposed method is based on coating thin layers assembled of silver or golden clusters with a prominent precision accessible by modern possibilities of scanning probe microscopy.

2. Method
A new method for electro-induced deposition of metal clusters was based on a method local electro-induced lithography by atomic-force microscope (AFM). The substrate is a p-type silicon with
surface roughness about 0.2 nm. The local relief was formed along the trajectory of a conductive AFM probe by local electric-induced dissociation of a water solution of a metal salt in the saturated layer on the silicon. A bias voltage between the AFM tip and the sample was applied. Deposition was carried out in air at room temperature with an atomic-forces microscope platform based nanolab NTEGRA Aura probe in contact mode (see fig.1). We choose the silica as a material for deposition substrate because of the great importance of silica-based devices in a context of fabrication of all-optical photonic circuits.

![Fig. 1 The scheme process of AFM litography.](image)

The average thickness (varied from 0.7 to 4 nm) of the obtained structures is well controlled with bias voltage applied between the tip and the sample. The average value of the track width determined by the diameter of the water meniscus between the conductive probe and the silicon. It was not more than 100 nm (see Fig.2) which is much less then optical wavelength. It indicates that single metal tracks fabricated with proposed method allows for a tight concentration of an optical energy in a plasmon mode.

The ability to use thin and narrow metal stripes placed on dielectric substrate as plasmon waveguide was repeatedly demonstrated both experimentally and theoretically [4]. Although a lot of different schemes of metal plasmon waveguide fabrication was proposed recently, the goal of engineering of integrated all-optical plasmonic circuits still represents an open challenge.

Figure 2 demonstrates how complicated schemes of plasmon-supported waveguides can be fabricated using proposed technique. The structure shown on Fig. 2 is an array of the net of square cells split by thin metal stripes. Since the period between the stripes can be kept in order of optical wavelength (400 nm in Fig. 2b), such a structure represents promising platform for fabrication of two-dimensional metallic photonic crystal for a plasmon excitations propagating along the stripes – cf. with [5]. Besides the obtained grating could be coupled to an optical waveguide mode propagating in the substrate. Such systems are known for their narrow-band optical response [6] and are rather sensitive to a change of environmental refractive index which induces spectral shifts of supported plasmon resonances of the structure.
Fig. 2 The AFM-image of silicon substrate after lithography at a voltage 8 B (a) and the profile of silver deposited clusters along the line (b).

Also, width and uniformity of the filling pattern of silver can be increased by repeated passage of the probe from a given area (Fig. 3). These structures can be used as a possible hybrid circuits for photoelectron transducers.

Fig. 3. AFM-image and 3D-image clusters: 3 passes (a) 1 pass (b)
Because the relief height isn’t more than ten nanometers, such structures in the vertical direction should be transparent to the optical radiation. While in the plane of the nonlinear light interaction occurs due to the coincidence of the lattice period, the frequency of the plasmon resonance of silver/gold and a waves excitation on the interface of silicon-metal. Such structures can be applied as optical microcavity and logical element (see fig.4)

Fig. 4 The AFM-image of golden massive on silicon substrate after AFM lithography at bias voltage about 8 B (a) and and its profile (b)

The structure shown on Fig. 4 represents the arranged ensemble of bowtie gold nanoantennas. Such structures are known for their tight concentration of electromagnetic field which enable for an enhancement of emission rate of a structure embedded between the tips of a single bowtie. Due to dense concentration of a bowties in a massive the neighboring structures become coupled in the sense of tunnel coupling between adjacent bowties. This coupling modifies the optical response of fabricated structure.

3. Conclusion
The method of electro-induced deposition of metallic layers on the silicon substrate is offered. The formation of planar structures for photonics is discussed.

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