Spatial confinement of the optical Tamm states under patterned metal films

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Abstract. Optical Tamm states are defect electromagnetic modes which appear at the discontinuity of the optical crystal. Being trapped at the interface of a dielectric Bragg mirror and a metal they demonstrate a tight localization in the direction perpendicular to the interface. Here we study the trapping of the Tamm states in the interface plane by patterning of the metal layer. In particular, we propose a method of metal film deposition based on a electro-induced lithography which possesses a nanometer lateral resolution.

1. Introduction
The presence of defect electron states at the crystal surface was first predicted by Tamm in 1932 [1] and later studied by Shockley [2]. These states appear as a regular solution of the Schrodinger equation with a periodic potential with broken translation symmetry. Therefore they reside any finite size crystal. However, being inconceivably difficult to detect these states had been remained unobservable for a long time. That is why the first experimental investigation of the electronic surface states was performed with a semiconductor superlattice instead of the conventional crystal [3].

A new life into the studying of Tamm states was breathed by transferring this concept from the solid state into optics, where the localized electromagnetic modes can be easily excited and detected. At the beginning, it was demonstrates [4] that the optical Tamm state (OTS) appears at the interface of two distinct distributed Bragg reflectors (DBRs) provided that their stop-bands overlap. Later this idea was renovated by replacing one DBR with the layer of metal [5-8]. Being confined in the DBR due to its photonic stop band, and in the metal due to its negative dielectric constant, the optical Tamm states combine a low mode volume with a respectable quality factor. For the apparent similarity to the surface plasmon modes these states are often referred to Tamm plasmon-polaritons or just Tamm plasmons. The most attractive feature of optical Tamm states are their dispersion. Unlike in the case of conventional surface plasmons, it is localized inside the stop band of the DBR and is intrinsically parabolic. Thus, the optical Tamm states possess an in-plane wave vector lying inside the light cone and can therefore be directly excited by the external light even at the normal incidence.
With the exception of some specific configurations [8] OTS are usually considered in the continuous 2D structures. In the configuration of the DBR covered with the metal it corresponds to the presence of a continuous metal layer. In spite of the fact that there were several proposals to utilize the localized OTS, i.e. those which are confined under the patterned metal structure [9-13], the influence of the discontinuity in the transverse direction on the properties of OTS remained undiscussed so far. The modification of the dispersion of the OTS by the patterned metal layer in the quasi-one-dimensional geometry formed by the narrow metal stripe deposited on the BM surface was studied in [14]. There were demonstrated that the energy and the losses which a linked to the propagation length of the studied waveguide modes are strictly dependent on the width and the thickness of the stripe. Thus the presence of a metal locally modifies the energy of the OTS and is responsible for its trapping in the lateral direction. The case of 1D confinement is of particular importance because, on the one hand, it is simple and, on the other hand, the results obtained for 1D system can be generalized to a more complex case of 2D confined TPs.

Here we propose an efficient method of deposition of metal patterns on the top of the dielectric substrate. The proposed technique allows to fabricate metal structures of an arbitrary shape with a nanometer control over both the width and the thickness of the metal stripes. This study paves the way to the designing of a complicated optical circuits based on the OTS.

2. Deposition of patterned metal films on the BM surface
The discontinuity of the metal deposited on the top of DBR affects the properties of OTS in both TE and TM configuration which demonstrate a keen dependence of the energy on the geometric parameters of the stripe [14]. The lateral size of the metal pattern makes the main contribution to the confinement. In particular the trap gets deeper as the width of the pattern reduces. At the same time the mode lifetime increases since the light leaks from under the metal to the unpatterned region being emitted to the free space. In fact, for a sub-wavelength metal pattern such a loss mechanism becomes dominating leading to the steep increase of the loss rate. Thus the optimal size of the metal pattern which is a trade-off between the demand of a deep confinement and low losses should be about few units of a wavelength. At the same the thickness of the metal layer should not fall short of tens of micrometer in order to prevent the leakage of the light through it.

All the aforementioned requirements are satisfied by the proposed approach which is discussed below. The method is based on a local electro-induced lithography technique which is based on the use of an atomic force microscope (AFM) [15-17]. The main advantage of AFM related to the probe lithography is an ultimate precision in the nanoscale domain since the shape of the deposited film follows
the trajectory of a conductive AFM probe, see the sketch in figure 1. The surface of the top dielectric layer of the BM is covered with a water solution of a silver salt (\(\text{AgNO}_3\)). If the conductive tip of the AFM approaches the surface, the absorbed layer gets in touch with the probe and a water bridge is formed due to the capillary effect. An application of an electric voltage between electrodes represented by the tip and the wetted substrate initiates the electrochemical reaction in the bridge. In particular, the voltage triggers the process of dissociation of a silver salt into an ion of a metal (\(\text{Ag}^+\)) and a volatile gas (\(\text{NO}_2\)) in the area around the tip. Then silver ions are assembling into clusters which grow and eventually form a solid layer of metal directly under the tip. The slow lateral movement of the tip allows for the formation of long and homogeneous patterns.

Figure 2. (a) – the AFM-image of the pattern made of silver on the surface of the GaAs/AlGaAs BM. The AFM lithography was performed under the bias voltage of 8 V and with 25 passages. The layer of a 2 nm thickness was formed at each passage. (b) – the same as in (a) but in 3D view.

Figure 2 shows an example of a complicated Tamm-plasmon-supported structure which was fabricated using the proposed technique. The deposition was carried out at a room temperature with a nanolab NTEGRA Aura operating in a contact mode.

The in-plane resolution of the proposed method is governed by a positioning accuracy of an AFM which can reach fractions of nanometer. However the minimum size of the fabricated metal structure is limited by a diameter of the water bridge between the conductive probe and the substrate. For instance, for DCP11 probe it is about 100 nm. The further reduction of the tip size would lead to the shrinking of the water bridge down to the limit set by the viscosity of the salt solution and the surface tension in the bridge. In what concerns the fabrication of TP supportive metallic stripes and their networks, the sizes inferior to the wavelength of light are not relevant. In order to control the thickness of the metal film the structure should be grown layer by layer by multiple repetitions of the described process. The thickness of a single layer is well controlled by the bias voltage (in the range of 6-10 V) and the scanning velocity. For the considered design, the thickness is tunable in the range from 0.7 to 4 nm. The upper limit is imposed by the saturation of the deposition processes due to the local depletion of the non-dissociated metal salt beneath the tip.

3. Conclusion
The presence of metal layer provides a convenient platform for confinement and management of the energy of OTS while the presence of a DRB is responsible for the low level of losses. Patterning of a metal layer allows for an easy and precise way to constraint TP mode in the lateral direction. For the purpose of engineering of the confinement of TPs we propose a method of the metal film deposition
based on the electro-induced lithography technics. It allows for a high precision control of the energy of TP by the variation of the metal layer thickness and of the width of the patterned structure. The proposed method is better adapted for fabrication of TP networks than the etching techniques. The etching introduces a microroughness to the structures thus causing addition losses while the AFM-assisted electro-lithography discussed in this work possesses a nanometer precision.

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