Properties of a Tamm plasmon structure with a sub-wavelength ring-shaped structuration

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Abstract. We have used the finite element method to demonstrate numerically that losses in Tamm plasmon structures can be reduced, and Tamm resonance parameters can be tuned using a sub-wavelength ring-shaped structuration of the metal layer. The axisymmetric structure consists of a GaAs/AlₓGa₁₋ₓAs Bragg reflector covered with a sub-wavelength ring. The results demonstrate that the quality factor of the Tamm plasmon mode with a ring of given parameters increases substantially. In addition, we have compared the properties of the structure with two different resist materials (PMMA and CSAR 62) and demonstrated a shift in the resonance frequency of the Tamm plasmon mode for each case.

1. Introduction

Tamm plasmon is a novel electromagnetic state localized at the interface between a metal and a specially designed Bragg reflector, the existence of which was recently predicted and experimentally demonstrated [1,2]. Tamm plasmon modes form in both TE and TM polarizations inside a light-cone, demonstrate lower losses than conventional plasmon modes, and open up new ways to use plasmonic parts in potential applications and devices [3, 4, 5].

However, despite the progress in the study of Tamm plasmons and many potential applications in modern devices, the main obstacles to improving the performance of Tamm plasmon modes in lasing optoelectronic devices are the losses and heating of metallic parts due to strong absorption, as in other plasmonic structures [6]. A number of experimental studies of structures based on Tamm plasmons are aimed at the reduction of losses in metal by structuring the metal layer [7, 8].

One of the approaches to reducing losses is to use a formation of subwavelength elements on the metallic layer. This paper is aimed at a theoretical analysis of the properties of the ring-shaped Tamm plasmon structure, namely, the ability to tune the position of the Tamm plasmon resonance and the quality factor in cylindrical geometry. By tuning the geometrical characteristics of the subwavelength ring, it is possible to obtain a mode with a high quality factor due to greater confinement compared to the usual Tamm plasmon structures.
2. Results and discussion

We investigate a Tamm plasmon structure with a ring-shaped subwavelength structuration of the covering metal layer. We chose gold in our study. A distributed Bragg reflector (DBR) consists of 30 pairs of GaAs/Al\textsubscript{0.95}Ga\textsubscript{0.05}As quarter-wavelength layers with a GaAs layer on the top. We consider two different types of positive resists generally used in the high-resolution electron-beam lithography: PMMA (polymethyl methacrylate) and CSAR 62 (poly (\(\alpha\)-methyl styrene-co-\(\alpha\)-chloroacrylate methylester)). PMMA and CSAR 62 have different refractive indexes (1.5 and 1.67, respectively), which affects the resonant properties of the Tamm structure. The ring-shaped Tamm structure layout and its cross-section are shown in figure 1. We considered a single-ring structure with a width related to the radius of the cylindrical DBR as \(R/\xi\), where \(\xi\) is the ratio between areas of the ring and the whole structure. Thus, for small values of the \(\xi\) factor, the structure will be the same as a normal Tamm plasmon structure with an additional resist layer under the gold layer. For high values of the \(\xi\) factor, the structure represents a Tamm structure with a thin subwavelength ring on the top. A set of numerical simulations was performed to understand how the ring shape influences the Tamm plasmon mode structure in the current geometry.

![Figure 1](image_url)

**Figure 1.** (a) Schematic diagram of the subwavelength ring-shaped Tamm plasmon structure. (b) Diagram of the cross-section of the subwavelength ring-shaped Tamm plasmon structure.

The three-dimensional (two-dimensional axisymmetric) problem was considered using the finite element method (FEM) in the COMSOL Multiphysics modelling environment. The gold layer was 45 nm thick, and the resist layer (in both cases) was 90 nm thick. Reflection spectra were calculated for each structure with different \(\xi\) factors. The excitation was performed using the fundamental TE polarized circular wave. The frequency position of the Tamm resonance and the quality factor were estimated from the obtained spectra by fitting the Tamm resonance (using the Lorentz function).

The results of simulations are shown in figure 2. Figure 2 (a) demonstrates the dependence of the quality factor of the Tamm plasmon mode and the resonance wavelength on the ring size (\(\xi\) factor) with two types of resist. As shown in figure 2 (a), the spectral position of the Tamm plasmon resonance can be efficiently tuned by changing the \(\xi\) factor for both resist materials. This result is similar to the two-dimensional case considered in [7]. The Q factor in our research reaches values significantly higher than in the two-dimensional case even with the added structuration. The maximum value of the quality factor is 2732 for PMMA resist at \(\xi = 3\) and 2282 for CSAR 62 resist at \(\xi = 3.5\). When the \(\xi\) factor goes over 5, the Q factor starts to decrease. This can be explained by the fact that at high \(\xi\) the ring size becomes insignificant compared to a metal coating part. Figure 2(b) demonstrates the electric field distribution in the half cross-section of the structures. In the case of \(\xi = 7.5\) the
overlap of the electric field of the Tamm plasmon mode with the metal is higher than in the case of $\xi = 1.25$. It is also evident that the electric field at $\xi = 7.5$ has a more specific profile than at $\xi = 1.25$. This could be explained by coupling of the Tamm plasmon mode with another cylindrical mode due to the geometry of the problem.

Figure 2. (a) Dependence of the Tamm Plasmon quality factor (left axis) and resonance wavelength (right axis) on the $\xi$ factor for tPMMA (open circles) and CSAR 62 (solid circles). (b) Calculated electric field $|E|$ [V/m] in the half cross-section of the structures at $\xi = 1.25$ (top figure) and $\xi = 7.5$ (bottom figure) for the PMMA resist case.

3. Conclusions
Properties of a Tamm plasmon structure (GaAs/Al$_{0.95}$Ga$_{0.05}$As DBR with a gold coating layer) with the sub-wavelength ring-shaped structuration and two different resist materials (PMMA and CSAR 62) were analyzed theoretically. A set of FEM electromagnetic simulations were performed with different parameters of the gold/resist ring structure. The formation of a sub-wavelength ring element with given parameters in the coat part of the Tamm plasmon structure can significantly increase the quality factor of the Tamm plasmon mode.

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