Quality factor enhancement in gold-based Tamm plasmon cavity by sub-wavelength structuration

A R Gubaydullin¹,², K M Morozov¹,², M A Kaliteevski¹,²
¹St. Petersburg Academic University, St. Petersburg, 194021 Russia
²ITMO University, St. Petersburg, 197101 Russia

Abstract. We have demonstrated theoretically using a finite elements method that losses in Tamm plasmon structures can be reduced by using a sub-wavelength structuration of the metal layer. The structures consist of a GaAs/Al₀.₉₅Ga₀.₀₅As Bragg reflector covered with a sub-wavelength golden grating. The results demonstrate that the quality factor of the Tamm plasmon mode with grating increases substantially, with respect to the similar structure without a grating. Also, we have demonstrated that resonance frequency of Tamm plasmon mode can be tuned by varying the filling factor parameter.

1. Introduction

During the past decade, there are growing interest of researchers to nanostructures where Tamm plasmon modes can be realised. Tamm plasmon is an electromagnetic state localized at the interface between the metal and the specially designed Bragg mirror was predicted recently [1]. Tamm plasmon provides new possibilities for utilizing metallic parts in modern optoelectronic devices. Tamm plasmon modes are forming in both TE and TM polarizations and demonstrate lower losses than conventional plasmon modes. Recently, polarization-controlled confined Tamm plasmon lasers [2] and control of spontaneous emission rate of quantum dots placed in Tamm structure [3] have been demonstrated.

Despite progress in study of Tamm plasmons and many ways of potential applications of them in modern devices, the main obstacles of improving performance of Tamm plasmon modes in lasing optoelectronic devices are losses and heating of metallic parts due to absorption as in the others plasmonic structures [4]. A number of experimental studies on plasmonic devices aimed at the reduction of losses in metal by structuring the metal layer. One of the approaches to reduce losses is a formation of a subwavelength grating on the metallic layer.

This paper is aimed at theoretical analysis of the possibility to tune the Tamm mode resonance position and quality factor by covering the distributed Bragg reflector (DBR) with a periodical golden sub-wavelength grating.
2. Results and discussion
The structure under study is Tamm plasmon structure with the sub-wavelength structuration of the covering golden layer (figure 1). Conventional Tamm Plasmon structure is based on the distributed Bragg reflector (DBR). In our case DBR consists 30 pairs GaAs/Al$_{0.95}$Ga$_{0.05}$As quarter-wavelength layers with high refractive index GaAs layer on the top (to realize electromagnetic field localization on the edge between metal and DBR). Scheme of the structure is shown in figure 1 (a). To reduce absorption in the metallic layer the sub-wavelength grating on the top of DBR could be formed [5]. Here we consider parameters and materials generally used in fabrication of sub-wavelength gratings by electron beam lithography– polymer resist material PMMA (polymethyl methacrylate). We investigated a series of Tamm plasmon structures with gold-PMMA gratings with different ratio of filling factors. The grating could be defined by two parameters: a period (in our case it’s 250 nm) and a filling factor (ff), i.e. relation between thickness of a golden part of a grating period to a PMMA part. For instance, when the filling factor is 50% it means that half of the period (125 nm) is covered by the golden layer and another half is covered by the PMMA layer with gold on the top (figure 1 (a)). Therefore, we are analyzing how the presence of the grating with different filling factors influence on the properties of Tamm plasmon mode: the resonance frequency position and the quality factor.

Two-dimensional electromagnetic simulations were carried out using a finite element method (FEM) in COMSOL Multiphysics modelling environment. The thickness of the golden layer is 45 nm, and the thickness of the PMMA layer is 90 nm. Real and imaginary parts of a gold refractive index was obtained by fitting the experimental data of Johnson and Christy [6]. Reflection spectra were calculated for each structure with different filling factor in case of TE polarized wave and normal incidence. From obtained spectra we estimate the frequency position of the Tamm resonance and the quality factor by fitting the Tamm plasmon resonance by using the Lorentz function.
Figure 2(a, b). (color online) (a) Dependence of Tamm Plasmon resonance frequency on filling factor. (b) Dependence of investigated Tamm plasmon cavity quality factor on filling factor.

Results of simulations are demonstrated in figure 2. Figure 2 (a) demonstrates how the Tamm plasmon resonance wavelength depends on the filling factor. We observe the maximum resonance shifting around 42 nm, when filling factor is 0%. Figure 2 (b) shows the quality factor dependence on the filling factor. The quality factor increases substantially while decreasing the filling factor (which also means a decrease of the gold/GaAs contact area) due to reduced absorption in the metallic layer. Dependence has maximum value of the Q factor =811 at the filling factor value = 6%. Relatively high quality factor values (more than 650) could be achieved in structures with filling factors less than 20%. In structures with filling factors more than 60% influence of sub-wavelength structuration is insignificant due to the dominant losses in metal.

3. Conclusions
We provided theoretical analysis of the sub-wavelength structuration influence on the properties of Tamm plasmon structure formed by GaAs/Al_{0.95}Ga_{0.05}As DBR with the gold metal coating layer on the top. Several FEM electromagnetic simulations were carried out with different parameters of the golden layer structuration. We demonstrated that the resonance frequency of Tamm plasmon mode can be tuned by changing the filling factor parameter. Realisation of the sub-wavelength structuration in Tamm plasmon structure can significantly increase the quality factor of Tamm plasmon mode.

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