Effect of metallic nanoantennas on the efficiency of the surface plasmon-polariton generation via excitation of electromagnetic waves in a tunnel junction

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Abstract. Inelastic tunneling of electrons can be used for generation of the surface plasmon-polaritons (SPPs). In this paper, we study numerically the surface waves generation during the electrons tunneling through the barrier between tip of the scanning-tunneling microscope probe and golden substrate. To study the process the emission of the tunneling electrons was approximated with an optical dipole emission. First, we demonstrate that the efficiency of the SPP generation in terms of energy conversion cannot exceed 1 % when no antenna is present in the system. We then carry out the simulation of the SPP generation when the probe tip is in a close proximity with the golden nanoantenna in the shape of sphere or cylinder. We show that the surface plasmon-polariton generation efficiency can be increased more than two orders of magnitude with the use of nano-antennas. Nanoantennas in the form of spherical nanoparticles are found to be more effective for the SPPs generation than nanoantennas in the shape of cylinders.

1. Introduction

Inelastic tunneling of electrons can be used for generation of the surface plasmon-polaritons (SPPs). In this paper, we study numerically the surface waves generation during the electrons tunneling through the barrier between tip of the scanning-tunneling microscope probe and golden substrate. To study the process the emission of the tunneling electrons was approximated with an optical dipole emission. First, we demonstrate that the efficiency of the SPP generation in terms of energy conversion cannot exceed 1 % when no antenna is present in the system. We then carry out the simulation of the SPP generation when the probe tip is in a close proximity with the golden nanoantenna in the shape of sphere or cylinder. We show that the surface plasmon-polariton generation efficiency can be increased more than two orders of magnitude with the use of nano-antennas. Nanoantennas in the form of spherical nanoparticles are found to be more effective for the SPPs generation than nanoantennas in the shape of cylinders.

2. Numerical modeling

We calculated the axially symmetric problem of the STM probe tip with a metallic surface interaction in Comsol Multiphysics program. In the proposed model, the radiation in the tunnel junction was
approximated with the emission of an optical dipole having vertical polarization. The presence of the STM probe and its influence on the waves propagation was not considered in the study. The location of the point dipole was fixed at a distance of 1 nm from the gold half-infinite substrate surface. The efficiency of the radiation in a tunnel junction was considered in the first part of the study. For this purpose, the ratio of all the propagating emitted electromagnetic waves energy (the sum of the plasmon and scattered waves) to the dipole source radiation power was investigated. The obtained spectral dependence of this ratio in the frequency range from 200 to 600 THz is shown in figure 1. Each point of the graph corresponds to the efficiency of the waves generation at a fixed frequency of the dipole radiation. As can be seen from the graph in figure 1 the efficiency of the dipole source energy conversion into the energy of propagating waves has a spectral maximum of 1 % at 400 THz. In this case, most of the energy goes into the structure heating.

Figure 1. The ratio of all the propagating waves power to the dipole source power.

In work [8] it was shown that positioning of a gold nanoantenna in the shape of a nanorod having diameter \( D = 21, 25 \) and \( 31 \) nm and height \( H = 51 \) nm in the tunnel junction under the tungsten STM tip increases the plasmon wave generation efficiency. To study this effect in our work we simulated the propagation of electromagnetic radiation from a point dipole source when the spherical \( (D = 60 – 300 \) nm) and cylindrical \( ( \text{where } D = 60 – 300 \) nm) nanoantenna are located on the surface of gold substrate.

To comprehensively study influence of the nanoparticle shape and dimensions on the SPP generation in the modeling we varied the geometry of the nanoparticles: in case of a gold sphere nanoantenna its radius was varied from 30 nm to 150 nm and in the case of cylindrical nanoantenna the radius and height values were modeled in the same range. Figure 2 (a) shows the spectral dependence of the ratio of scattered and plasmon wave energies sum to the dipole emission energy evaluated for the spherical gold nanoantenna in a wide dimensions range. The graph shows that the maximum efficiency can be achieved in the frequency range from 350 to 450 THz with the corresponding maximum generation efficiency of 30 %. In case of cylindrical Au nanoantenna the maximum efficiency can be obtained in the 400 to 450 THz range and takes the value of 22 % it show figure 2 (b). These maxima most likely correspond to the nanoantennas resonance with the dipole emission at small nanostructure radius of 30 – 60 nm.

Figure 3 shows the graphs of the efficiency of the dipole energy conversion into SPP energy in presence of nanoantennas. Comparing the graphs in figure 2 and figure 3 we can see that most of the source energy is directed at plasmon wave generation. It is also shown, that the spherical Au nanoantenna provides 30 % higher efficiency compare to the cylindrical Au nanoantennas.
Figure 2 (a, b). The energy conversion efficiency to the sum of scattered and plasmon waves evaluated for the spherical Au nanoantenna (a) and for the cylindrical Au nanoantenna (b).

Figure 3 (a, b). Efficiency of the source energy conversion into the plasmon wave evaluated for the spherical Au nanoantenna (a) and for the cylindrical Au nanoantenna (b).

To demonstrate the effect of enhancement of the SPP generation using nanoparticles the comparison between the cases of presence and absence of the antenna was carried out. Figure 4 shows the ratio of plasmon wave energy in the presence of nanoantenna (spherical and cylindrical) to the sum of plasmon and scattered waves energy without nanoantenna. Considering the case with Au sphere the maximum enhancement was found to be 400 times and in the case of a cylindrical nanoantenna its value was 120 times. Concluding, it was shown that the introduction of a nanoantenna into the tunnel gap junction leads to increase of the excitation efficiency of the surface waves and efficiency of the SPP generation using a metallic spherical nanoantenna with radius $R = 30$ nm is more than 3 times higher than of a cylindrical nanoantenna.
3. Conclusion

To conclude, the numerical modeling of the SPP generation via excitation of the electromagnetic waves in the tunnel junction between STM probe tip and metallic substrate with and without the nanoantenna was carried out. The optimal geometric parameters of the metallic nanoantenna, corresponding to the most efficient excitation of the SPP wave propagating along the gold substrate surface were obtained: for both spherical and cylindrical antennas the optimal radius value is 30 nm at 450 – 500 THz. The comparison of the energy conversion efficiency of a dipole source to a plasmon wave demonstrates strong enhancement with the use of nanoantennas.

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