STM Light Emission and I(V) study of single gold nanoantenna

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Abstract. High-speed optical nanoemitters are of importance for on-chip optical data processing. A tunnel junctions can be a base for such light emitters, however such structures suffer from low quantum efficiency. One of the ways to improve efficiency of tunneling electron energy to photon generation conversion is the increase of the local density of optical states by using of optical nanoantennas. In this work, we study optoelectronic properties of single gold nanodisc with high spatial resolution. We show nonuniform distribution of electromagnetic near-fields of nanodisk, which is consistent with nanoantenna optical modes. And we demonstrate direct correlation between nanoantenna optical states and features on current-voltage characteristics of tunnel junction between metal tip and nanodisk.

1. Introduction

The optical communication transfer enormous amount of information and this volume grows every year at the rate of 20-30% [1]. Optical links are one of the best ways to transfer information on large distance. At the same time metal wires are commonly used for data transfer within the parts of integrated circuits. Optical signal processing has many advantages, including the absence of ohmic losses and big speed of signal propagation. Transition to photonic can be next step of computing systems’ development. Currently, the size mismatch between nanophotonic components, CMOS-components and optical sources is a technological bottle neck. Available today light emitting sources, such as VECSELs, Fabry-Perot lasers or microcoring and microdiscs lasers, have resonators with minimal sizes significantly exceeding their emission wavelengths. Also, new type of optical sources is required to high frequency modulation. One of ways to overcome this size mismatch can be based on the use of inelastic electron tunneling process causing light emission. This phenomenon enables to create subwavelength light sources.

A process of light emission in the metal-insulator-metal (MIM) structures was discovered by the first time by Lambe and McCarthy in 1976 [2]. However, quantum efficiency (QE) of this process is very low (10e-6 – 10e-4 photon/electron). In recent years, there has been renewed interest in light
emission from tunnel junctions. Many articles were focused on the improvement of light emission from a tunnel junction [3–5]. It was shown that QE can be enhanced by increasing of local density of optical states (LDOS) in the tunnel junction. Theoretically, the value of QE may reach 10% [6,7] due to a large LDOS enabled by plasmonic confinement. Using of nanoantennas is a promising way to increase LDOS in the tunnel junction.

2. Experiment
Scanning tunnel microscopy (STM) is powerful tool for studying tunnel-junction light emission[8,9]. In this article, we used an ultra-high vacuum STM combined with a home-made optical setup. The experiment was produced in the STM Omicron VT650 with a vacuum not worse than 5e-9 mBar. The optical system consists of a small lens (d = 4 mm, N.A. = 0.32) positioned near the sample inside an STM vacuum chamber and the avalanche photodiode (IDQuantique ID120) with mirror system outside the vacuum chamber. The output signal from photodiode was directed to STM controller. It makes possible to acquire STM topography and obtain light emission map simultaneously.

We used STM to study the LDOS distribution of a single gold nanodisc by a Pt/Ir STM probe (DPT10, Bruker). The array of nanodiscs was made on thin gold film on mica substrate with low roughness[4]. The period of nanodiscs’ array was 1 µm. The nanodiscs produced by e-beam lithography have 50 nm height and 180 nm diameter.

![Figure 1](image1.png)

**Figure 1.** (a) Typical STM topography image of a nanodisc and (b) acquired light emission map.

We experimentally observed the increase of light emission under STM tip on edges of nanodiscs (Figure 1). As well known, the inelastic tunnel current is proportional to the integral of the density of optical states of the sample[9,10]. Therefore, we investigated current-voltage (I-V) characteristics at points on the line crossing the disk (Figure 2a). Figure 2b demonstrates I-V curves acquired at the edge of nanodisk. One can see the features on I-V dependence near 1.6 V and 2.2 V. The fingerprint map presented in Figure 2 c) shows d²I/d²V dependence for all points denoted at Figure 2 a). The features, which appear in the form of puddles on the color map, can be associated with inelastic tunneling and consequent light emission process [4]. This map allows to estimate the area of nanodisc with enhanced LDOS.

Also, we performed numerical simulation of the electromagnetic field distribution excited in a plasmonic nanodisc by a point vertical dipole, located between nanodisk and STM tip. The numerical simulation shows that two optical modes at 668 nm and 566 nm can be excited in the nanoantenna, when the STM tip located at the edge of nanodisk. At the same time with the probe positioned in the center of the nanoantenna, only one mode at 668 nm can be excited. Both modes have a «hot spot» at the edge of the nanoantenna, which confirms the increased LDOS at the periphery of the structure. This explains the increasing of the emission process efficiency from the tunnel contact, which was observed in the experiment (Figure 1 b). IV-curves analysis also shows a change of LDOS at the edge of the nanoantenna (Figure 2).
Figure 2. (a) STM topography image of a nanodisc with the markers enumerating the points of I(V) study. (b) Typical single I-V, d²I/dV² dependences measured at the edge of the disc (point #4). (c) d²I/dV² “fingerprint” map of the gold disc.

Also, optical spectra were measured on the same disks at ambient conditions. We use SmartSPM (AIST-NT) coupled with spectrometer Princeton Instruments SpectraPro-2500i (USA) equipped with PyLoN:400BR_eXcelon detector with liquid nitrogen cooling.

The optical spectra of the STM-induced nanoantenna emission contain two clear bands with maxima at 670 nm and 765 nm (Figure 3). The long-wavelength band dominates in the spectra obtained on the substrate between nanodisks (see green lines in Figure 3). While the short-wavelength band dominates in the spectra acquired on the nanoantenna (see blue lines in Figure 3). When the STM tip was located at the edge of nanodisk, optical spectra had the enhanced short-wavelength component. These experimental results qualitatively correspond to the results of numerical simulations, at the periphery of nanodisk the mode with shorter wavelength can be excited. We suggest that the difference of the peak spectral positions predicted by modelling can be caused by the changing of inelastic tunneling process compared to vacuum conditions, as well as the imperfections of disk fabrication. The simulation was performed for an ideal cylinder in vacuum, while in air the sample surface is covered with a thin layer of water, which affects the parameters of the tunnel contact, including the energy position of Fermi level. The low selectivity of mode excitation is most likely related to the relatively large diameter of the STM tip used, which is comparable with the size of the nanoantenna[11].

Figure 3. Radiation spectra of the tunnel contact obtained at different positions. The blue lines are spectra obtained from the tunnel contact with a nanoantenna. The green lines are typical spectra obtained from the gold substrate.

3. Results
The I-V and its second-order derivative curves of the tunnel contact allow to investigate optical modes nanoantennas with subwavelength resolution. It may be used for simplifying of the development of
nanostructures for local optical sources based on inelastic electron tunneling phenomena. In that case the use of optical detection system is not required. The proposed technique is essential for the development of electrically-driven plasmonic optical sources for on-chip optical data processing.

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