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# Investigation of the light emission in the local tunnel junction and its dependence on the contact surface morphology

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**Abstract.** In this paper we investigate light emission in a tunnel junction between a thin gold film on a glass substrate and a gold-coated tungsten tip of a scanning-tunneling microscope probe. The experiments show that the size of grains in the gold film surface dramatically affects the intensity of emissions. We demonstrate that a decrease in the grain aspect ratio provides an increase in the quantum yield of the tunnel-junction emission.

## 1. Introduction

The growth of the IT sector and corresponding developments in information processing have stimulated the emergence of new technologies. The next step in IT evolution is associated with the transition from electronic to photonic digital data processing. This step is one of the ways to overcome the performance bottleneck of current systems, which is related to a limited bandwidth and power density in modern semiconductor microchips. Today, optical signals are already used for efficient data transfer over long distances, but the use of optical communication between and on chips can increase the performance of existing computing systems [1].

One of the main problems for the forthcoming integration of technologies is the large difference in size between the existing photonic and electronic components. For the on chip data transfer semiconductor nanowires can be used playing as effective waveguides [2, 3]. True integration of photonic devices requires the development of a local nanosized photonic source. A traditional electrically driven photonic source is a semiconductor laser with a Fabry-Perot or microring resonator. These sources are not appropriate to be implemented on a chip due to their large minimum size, which is limited by the emitted wavelength.

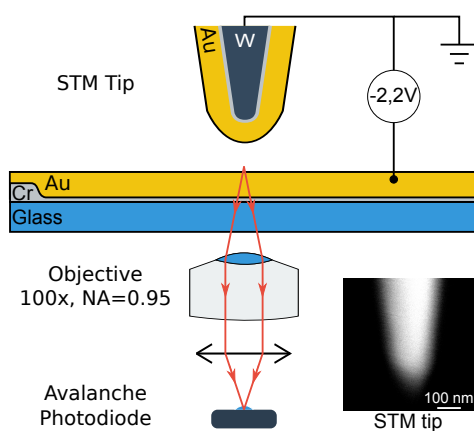
An alternative possibility for the development of a source of local light and surface-plasmon polaritons (SPP) is based on the effect of emission during inelastic electron tunneling. The phenomenon of light emission in a metal-insulator-metal (MIM) contact was discovered by Lambe and McCarthy in 1976 [4]. The gap size in the tunnel junction is sufficiently smaller than the wavelength. Consequently, such a junction may be used as a subwavelength light



source. The main problem in implementing this approach is a rather low quantum yield of the device ( $10^{-6} - 10^{-4}$  photon-per-electron). Thus, the enhancement of the tunnel junction efficiency is an extremely urgent task for the development of local photonic sources.

## 2. Experiment and samples

The scanning tunneling microscope (STM) is a powerful tool [5] appropriate for the study of tunnel junction effects. The experimental setup comprises a commercially available STM head operating in air (AIST-NT Combiscope) coupled with an inverted optical microscope as shown in figure 1. The emitted light was collected through a glass substrate with an Olympus objective lens (100x NA=0.95) and focused onto a single-photon counter (IDQuantique ID120) based on an avalanche photodiode.



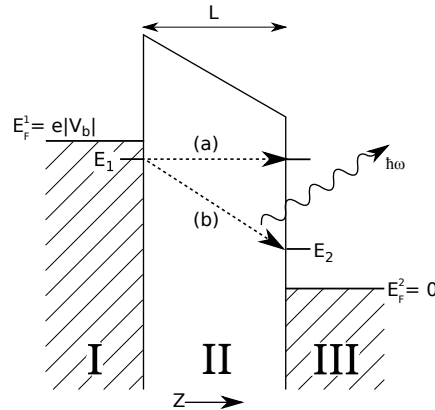
**Figure 1.** Schematic of the experimental setup. STM is integrated with an inverted optical microscope. The objective lens is focused on the tip-sample gap. The insert shows a SEM image of a typically used STM probe tip.

The tunnel contact was realized between a thick gold film and the STM tip. The tip was electro-chemically etched from tungsten wire (150  $\mu\text{m}$  in diameter) in KOH solution and coated with gold. The tip radius was about 50 nm according to the SEM measurements. The thick gold films were deposited on a 140  $\mu\text{m}$ -thick glass substrate with a thin chromium underlayer via thermal evaporation.

The light emission may be observed in a tunnel junction with an applied non-zero bias voltage ( $V_b$ ). Two processes occur in a tunnel junction with the current flow: elastic and inelastic electron tunneling (see the diagram in figure 2). In the first case, the electrons tunnel into empty states at the metal surface without interaction with the matter. In the second case, the tunneling electrons may lose their energy in the barrier region. The energy dissipation can lead to the emission of photons with energies less than or equal to  $e|V_b|$ .

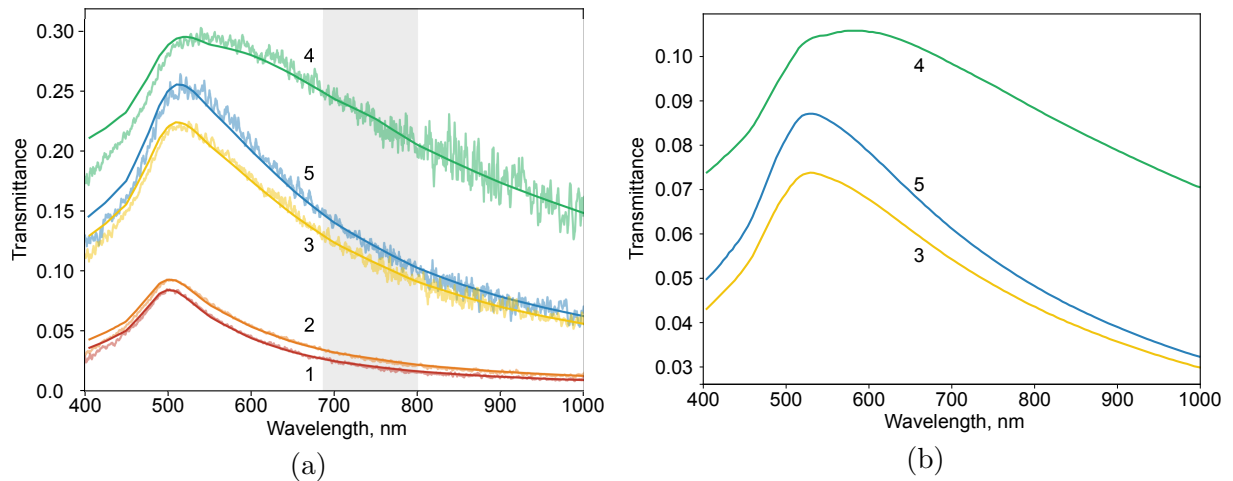
The visible photon emission may be obtained with 1.5-3 V of an applied bias voltage. The experiment was conducted at ambient conditions leading to the presence of a thin water layer (approximately less than 1 nm) covering the STM tip and the sample surface. This consequently leads to a water bridge formation in the gap between the tip and the sample [6]. The standard theoretical electrochemical potential for water electrolysis is 1.23 V, which is smaller than the bias voltage in our experiment. Therefore, there are two contributions in the total current between the tip and the sample, namely, the tunnel current and the ionic or Faradaic current of electrochemical nature [7].

During the experiments, the STM operated in the unstable regime, also known as the “saturation regime” according to [8]. This regime provides a higher quantum yield than the



**Figure 2.** Band diagram of a tunnel junction between two metals: **I** — the probe with an Au-coated tip; **II** — the potential barrier region; **III** — the Au film;  $E_F^1, E_F^2$  — the Fermi levels in regions **I** and **III**, respectively;  $L$  — the gap between the probe tip and the sample;  $E_1, E_2$  — the electron energies before and after the tunneling;  $V_b$  — the applied bias. The process (a) corresponds to elastic tunneling and the process (b) to inelastic tunneling with partial electron energy loss.

stable current regime. This regime is characterized by the oscillations of the sample under the tip leading to short current pulses. The feedback gain settings were set to provide the unstable regime. The sample was moved in the upper direction by a piezo stage until the contact was attained, and it was immediately moved down with the current detection. The frequency of the obtained oscillations was equal to 52 Hz. The emission intensity was measured using the same tip and settings of the feedback system in each experiment. The current setpoint was 165 nA, and the applied bias was 2.2 V.



**Figure 3.**

(a) The measured normal-incidence transmission spectra of samples ##1-5 (thin curves). The simulated transmission spectra fitted to the experimental data via variation of Au and Cr layer thicknesses (thick curves). (b) The simulated transmission spectra obtained with the excitation with a vertical point dipole placed in the vicinity of the sample surface. The numerical aperture of the capturing objective lens is taken into account. The numbering of curves corresponds to table 1.

The investigated Au films of different thicknesses have been deposited on a glass substrate using the thermal evaporation technique. The surface morphology of the samples was analyzed using atomic force microscopy. In accordance with the experimental setup, the emitted light was collected beneath the samples. For straightforward analysis of the emission, the optical transmission spectra were measured for each sample (see figure 3). The measured intensity was then normalized to the obtained transmission coefficient value at a wavelength of 740 nm. This value corresponds to the maximum on the gold-air-gold contact emission spectrum according to experiments with a similar setup [9].

To validate the measurements, numerical modeling was carried out. We modeled the penetration of the dipole emission through the substrate with a T-matrix. The dipole was placed close to the sample surface. The T-matrix modeling results are presented in figure 3. These results show good agreement with the experimental data.

### 3. Results and conclusion

The experimental results are presented in table 1. The enhancement of emission intensity with increased grain diameter ( $D_{grain}$ ) and decreased grain height ( $Z_{grain}$ ) is clearly demonstrated. The experiment shows that the intensity of the light emission in the gap dramatically depends on the grain aspect ratio. Since the tunnel junction emission quantum yield is rather low, the results of the study are very important for the development of an effective photonic nano-sized source.

**Table 1.** Parameters of the samples and experimental data

##	$h_{Cr}$ nm	$h_{Au}$ nm	$D_{grain}$ nm	$Z_{grain}$ nm	$A$	$I_n$
1	5.6	47	32	14	0.44	0.15%
2	6.1	43	40	14	0.35	0.44%
3	4.0	27	40	4	0.10	2.65%
4	4.6	16	60	4	0.068	3.76%
5	2.7	26	84	2.8	0.033	100%

$h_{Cr}, h_{Au}$  are the average metal film thicknesses;  $D_{grain}$  and  $Z_{grain}$  are the grain mean diameter and height, respectively;  $A = Z_{grain}/D_{grain}$  is the aspect ratio of grains;  $I_n$  is the normalized emission intensity.

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### References

- [1] Sun C, Wade M T, Lee Y, Orcutt J S, Alloatti L, Georgas M S and Moss B R 2015 Single-chip microprocessor that communicates directly using light *J. Nature* **528** 534
- [2] Dubrovskii V G and Bol'shakov A D 2012 Surface energy and modes of catalytic growth of semiconductor nanowhiskers *Tech. Phys. Lett.* **38** 311–5
- [3] Mozharov A M, Komissarenko F E, Bolshakov A D, Fedorov V V., Sapunov G A, Cirilin G E and Mukhin I S 2017 Modeling the semiconductor devices with negative differential resistance based on nitride nanowires *J. Phys. Conf. Ser.* **917** 082017

- [4] Lambe J, and McCarthy S L 1976 Light emission from inelastic electron tunneling *J. Physical Review Letters*, **37** 923
- [5] Timofeeva M, Bolshakov A, Tovee P D, Zeze D A, Dubrovskii V G and Kolosov O V. 2016 Scanning thermal microscopy with heat conductive nanowire probes *Ultramicroscopy* **162** 42–51
- [6] Boyle M G, Mitra J and Dawson P 2009 The tip-sample water bridge and light emission from scanning tunnelling microscopy *J. Nanotechnology* **20** 335202
- [7] Senftle F E, Grant J R and Senftle F P 2010 Low-voltage DCAC electrolysis of water using porous graphite electrodes *J. Electrochimica Acta* **55** 5148-53
- [8] Rogez B, Cao S, Dujardin G, Comtet G, Le Moal E, Mayne A and Boer-Duchemin E 2016 The mechanism of light emission from a scanning tunnelling microscope operating in air *J. Nanotechnology* **27** 465201
- [9] Parzefall M, Bharadwaj P and Novotny L 2017 *Quantum Plasmonics* (Cham: Springer) 211-36