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Fabrication of silicon optical nanoantennas by ultrahigh vacuum STM lithography

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Abstract. The paper reports on experiments on the observation of scanning tunnel microscope (STM)-induced light emission (STM-LE) from bare silicon surfaces and modified with STM lithography. We produced nanoscale hillocks (nanokhobs) on a crystalline Si substrate, which can be considered as nanoantennas enhancing STM-LE effect. Our experiments show that the nanoknobes formed on the surface of the original substrate did not provide the achievement of the goal. However, in-situ deposition of a 10 nm thick additional layer of undoped Si resulted in the increase of STM-LE quantum efficiency by an order of magnitude in comparison with original substrate. This effect paves the way for the fabrication of nanoscale electrically-driven light sources required for hybrid optoelectronic chips.

Keywords: scanning tunneling microscopy, tunnel contact, emission from a tunnel contact, silver film, photonics, ultrahigh vacuum

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Изготовление кремниевых оптических наноантенн методом сверхвысоковакуумной СТМ-литографии

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Аннотация. В статье сообщается об исследовании эмиссии света, индуцированной СТМ-контактом с чистой кремниевой поверхностью и модифицированной методом

СТМ-литографии. На поверхности кремния были созданы нанохолмы, выступающие в роли наноантенн, усиливающие эффект эмиссии света. Однако, они не обеспечили достижение поставленной цели. Тем не менее, осаждение дополнительного слоя нелегированного кремния толщиной 10 нм привело к увеличению квантовой эффективности по сравнению с исходной подложкой. Этот эффект позволит изготавливать наноразмерные электрически управляемые источники света, необходимые для гибридных оптоэлектронных чипов.

Ключевые слова: сканирующая туннельная микроскопия, туннельный контакт, излучение из туннельного контакта, серебряная пленка, фотоника

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Introduction

The growing importance of information technologies requires the continuous increase of data processing capabilities. The most common way to enhance computing performance consists in the use of multicore systems, which also helps to overcome the problem of the heat produced by processor chips. However, the total performance of multicore systems is often limited by the efficiency of interconnections [1], and this restriction becomes more severe with the increase in the number of cores. Conventional interconnections made of metal wires or cables have inherent limitations in bandwidth, transferred power density, and their length is restricted due to relatively high resistance. Interconnections based on optical links have no such limitations [2]. This approach is not yet widely used mostly due to the unsolved acute problem of miniaturization of optical sources, while other advanced small-size components of optical links are already developed and commercially available [3–5].

One of the possible ways to develop compact light sources is to use the phenomenon of light emission by tunneling electrons [6]. Tunnel junctions have sizes of the order of several nanometers [7] and they are capable to support high-frequency modulation. Until recently, all light sources based on metal-insulator-metal tunnel junctions had a critical drawback, i.e. their quantum yield was very low: typical values corresponded to the range of 10^{-6}–10^{-5} photons per electron. However, for the last decade it has been demonstrated that optical nanoantennas placed near a tunnel junction can substantially enhance the light emission, which renewed interest of researchers to this type of light sources.

In this paper, we report on the study of a method for the fabrication of silicon hillocks (nanoknobs) on silicon substrates. We have suggested that such features can act as nanoantennas enhancing light emission from tunnel contacts based on the metal tip of scanning tunnel microscope (STM) and the studied silicon features. The obtained results are essential for the development of complementary metal-oxide-semiconductor (CMOS) compatible electrically driven compact light sources.

Experiment

The experiments were performed in ultra-high vacuum (UHV) conditions in the chamber of a VT AFM XA 50/500 microscope (Scienta Omicron, Germany) which has been upgraded with optical scheme to allow the direct measurements of light emission from STM tunnel junctions (STM-LE). For STM experiments, we employed commercially available Pt/Ir-tips DPT10 (Bruker, USA). Single photon counter ID120 (IDQuantique, Switzerland) with spectral sensitivity in the range of 450–960 nm was used as an optical detector. The used experimental setup has been described in detail elsewhere [8].

The studied structures were formed on a silicon wafer with (001) surface orientation and high doping level (ca. 10^{19} – 10^{20} cm^{-3}). Before being loaded to STM chamber the substrate was cleaned in 20% HF solution for 5 minutes and then annealed in UHV vacuum at 120 °C for 45 minutes.

In our studies, the original silicon wafer showed STM-induced luminescence with the estimated quantum efficiency not higher than $5{\cdot}10^{-7}$ photons per electron (this result has been previously reported in [9]). This value can be improved by modification of tunnel gap morphology [10] or by introduction of an optical nanoantenna into the tunnel junction [8, 11]. We produced hillocks (nanoknobs) on the Si substrate by applying series of short voltage pulses with deactivated microscope feedback: STM lithography (see STM images in Fig. 1). The bias pulses have triangle shape with an amplitude from –7 V to +7 V and reversal. The duration of each pulse was 200 ms. Initial setpoint was 0.1 nA at 2 V and it was maintained between repetitions. It should be mentioned that nanoknobs are known to operate as optical nanoantennas enhancing STM-LE response [12]. However, our studies did not prove any notable change in the optical emission after surface modification.

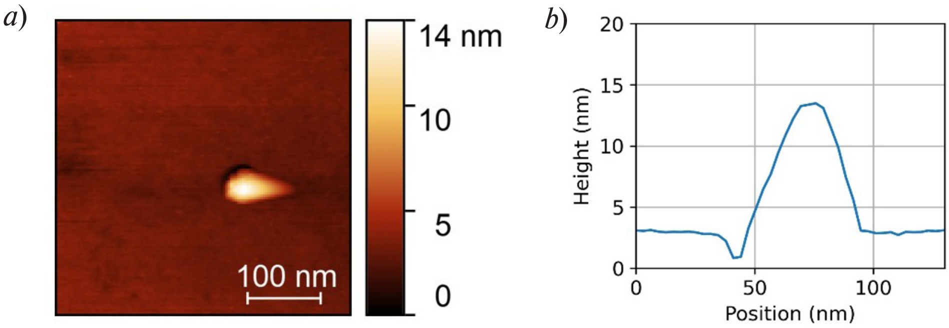

Fig. 1. Typical STM image of the obtained single nanoknob (white spot) on a Si substrate surface (a). Cross-section of single nanoknob topography corresponding to olive line on topography (*b*)

On the next step, inside the STM chamber, a 10 nm layer of undoped Si was thermally deposited on the patterned substrate and the set of nanoknobs was produced with the same STM lithography settings. The fabricated nanoknobs had the approximately the same shape as for the case of bare Si substrate.

Then, the STM-LE measurements were repeated, with bias voltage ramped between −10 V and +10 V while the tip position feedback was deactivated. In these experiments, quantum efficiency at 4.4 V bias was estimated as ca. $4{\cdot}10^{-6}$ photons per electron, which is approximately an order of magnitude higher than that for the sample without additional silicon layer (Fig. 2). We attribute this effect to STM-LE improvement caused by the enhancement of local density of optical states in nanoknobs [12]. The second peak at higher bias values observed in the quantum efficiency dependence in Figure 2 can have a different nature: we explain it by silicon nanostructuring

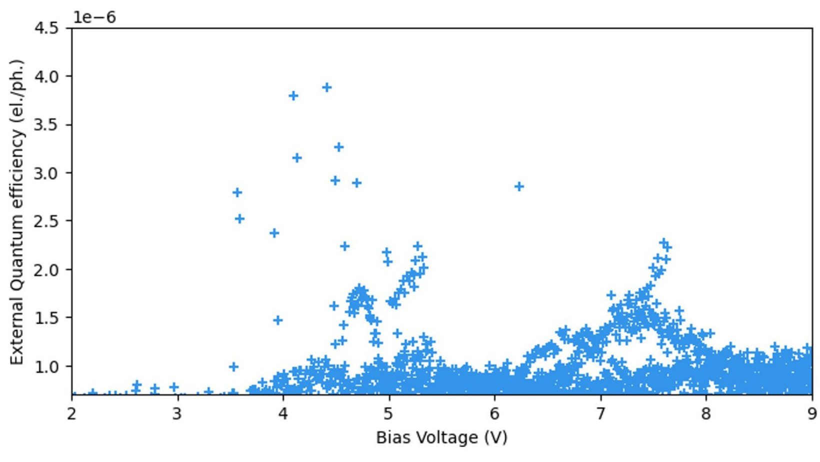

Fig. 2. A plot of estimated STM-LE quantum efficiency vs bias voltage for Si nanoknobs, measured for a tunnel junction between Pt/Ir STM tip and Si substrate with additional 10 nm Si layer

in the nanoknob improving its electroluminescence. At relatively high bias (exceeding 5.5 V) nanocrystals in Si can demonstrate electroluminescence in the visible spectral range due to direct charge carriers' injection and their recombination [13, 14].

Conclusion

The experiments performed have shown that quantum efficiency of the STM-LE on silicon surface can by increased by nanoscale local modification of the material. This technique can be used for the fabrication of CMOS-compatible nanoscale light sources demanded for the development of electro-optical integrated circuits.

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