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Heat Management and Quantum Efficiency Enhancement of Phototransistors Made from Two-Dimensional Materials

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Abstract: By placing a periodic array of metal nanoparticle-silicon nanowire composite structures underneath a monolayer of MoS_2, we achieve the design of a phototransistor with improved thermal management, higher quantum efficiency, and lower phase noise.

1. Introduction

In the last two decades, our interest has grown in utilizing two-dimensional (2D) materials for various photonic and optoelectronic applications including sensing [1]. Among these 2D materials, molybdenum disulfide (MoS_2) has attracted significant attention due to its promising optical, electrical, thermal, and mechanical properties [1–3] and in this work, our focus is on phototransistors made from a monolayer of MoS_2.

From an applied research standpoint, MoS_2-based phototransistors, illustrated in Fig. 1(a) have matured and their potential applications have been discussed in several publications. For example, Yin *et al.* achieved a photoresponsivity of 7.5 mA/W in a single-layer MoS_2 phototransistor [4], surpassing graphene-based counterparts. Lopez-Sanchez *et al.* extended photoresponsivity to 880 A/W at the wavelength of 561 nm [3]. Other investigations explored photoconductive and photogating effects, intrinsic optoelectronic characteristics, and ultra-high photoresponsivity when integrating 2D plasmonic crystals with the MoS_2 phototransistor [1]. Since these are atomically thin materials, some researchers have utilized plasmonic resonances to enhance light absorption by placing metal structures in the vicinity of the 2D materials. A typical choice is fabricating these plasmonic structures on top of the 2D material [5]. Even though this approach provides a large local field enhancement, it also leads to heating. In this work, we propose a novel design in which we achieve both local electric field enhancement (and hence an increase in the light absorption by the MoS_2 layer) as well as efficient heat management.

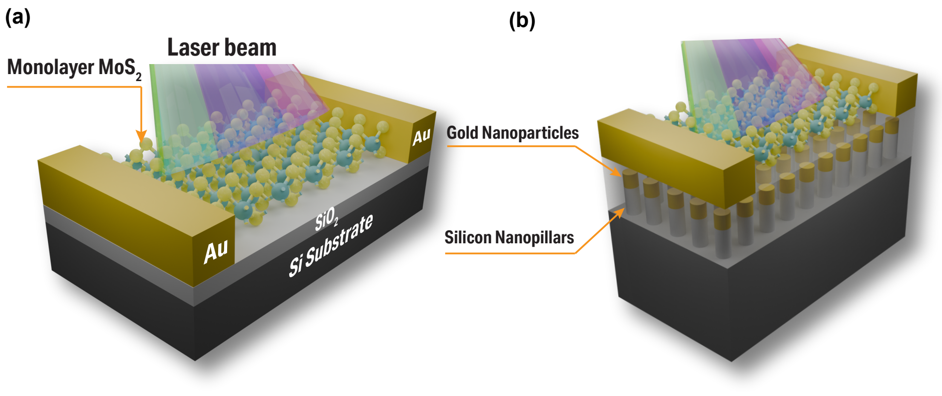

Fig. 1. Schematic illustration of (a) a plain monolayer MoS_2-based phototransistor and (b) the proposed design, where there is an array of Au nanoparticle-Si nanopillar composite structure underneath the MoS_2 layer.

2. Design Details and Numerical Results

Figure 1(a) shows a typical MoS_2-based transistor, where the SiO_2 and back-gated Si layers are 270 nm and 1 μm thick, respectively. The MoS_2 layer is 0.65 nm thick and 1 μm long. There are Au gates on each side to be used as source and drain. The structure is normally illuminated from the top. This simple phototransistor exhibits a 7% quantum efficiency when the wavelength of the laser is 561 nm [3].

Next, we place an array of Au particles (with a radius of 60 nm, height of 65 nm, and inter-particle spacing of 200 nm) on top of the MoS_2 layer and calculate the local fields, currents, and heat using both our numerical solver [6] and Ansys Lumerical, a commercial software package. The complex electrical permittivity of MoS_2 is calculated using the model developed in [2] as a function of temperature and Fermi energy level. When the power of the incident laser is 1 mW, the local temperature inside the MoS_2 layer reaches 550 K as shown in 2(a). Then, we place the Au nanoparticle-Si nanopillar array 5 nm underneath the MoS_2 layer as shown in Fig. 1(b). The Si nanopillars are 200 nm tall, and they have the same radius as the Au nanoparticles. In this case, the highest temperature is only 370 K as shown in Fig. 2 (b). In Figs. 2(c) and (d), we observe an increase of almost 25% in the quantum efficiency and output current, respectively. The phase noise, shown in Fig. 2(e), is nearly 30 dBc/Hz lower than the original design.

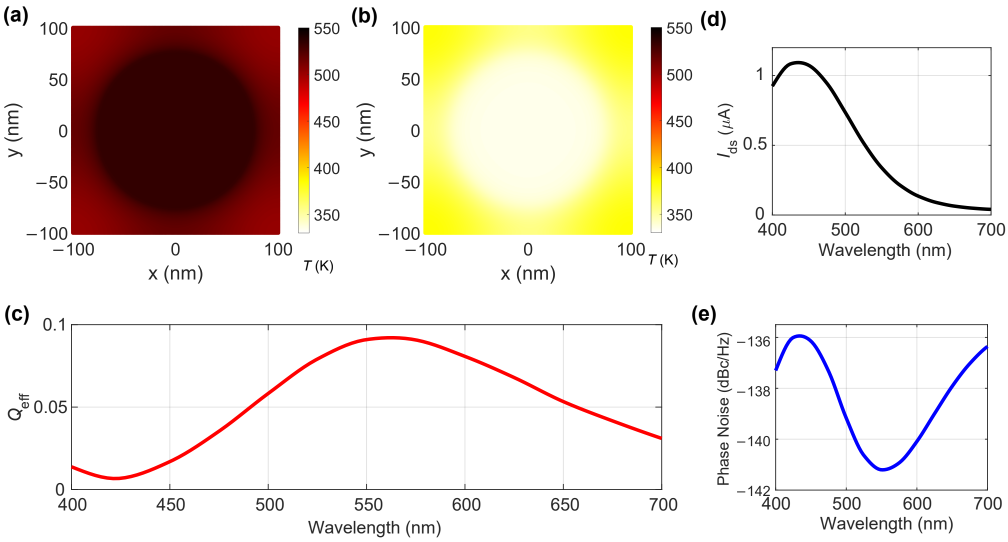

Fig. 2. Temperature inside the MoS_2 when Au nanoparticles are fabricated (a) on top and (b) in the proposed design when the phototransistors are illuminated with the same laser. (c) Quantum efficiency, (d) output current, and (e) phase noise of the proposed design as a function of excitation wavelength.

3. Conclusion

We enhance light absorption of MoS_2 plasmonically by placing a metal nanoparticle array underneath the MoS_2 layer. Due to their high thermal conductivity, the silicon nanopillars that support the metal nanoparticles, provide efficient heat flow and prevent heating. The proposed phototransistor has a higher quantum efficiency and lower phase noise compared to plain devices and devices where the nanoparticles are placed on top.

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