Excito-Plasmonic Phototransistors with Improved Thermal Management

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Metal nanoparticles (NPs) periodically arranged on two-dimensional (2D) materials are frequently employed to boost local electric fields and light absorption by the 2D material, particularly in photodetectors and light sources. However, this enhancement is often accompanied by significant temperature increases under high optical power. Here, we investigate the potential for a novel phototransistor design that achieves moderate field enhancement while simultaneously providing improved thermal management.

We previously developed a drift-diffusion model and validated it against experimental results to conduct detailed analyses of 2D material-based phototransistors [1]. This model assumed a constant operating temperature. Recently, we extended this model to incorporate local temperature changes arising from Joule heating [2]. After validating the accuracy of this extended model against experimental results found in the literature, we numerically investigate the performance of 2D material-based phototransistors decorated with metal NPs, which we call “excito-plasmonic phototransistors".

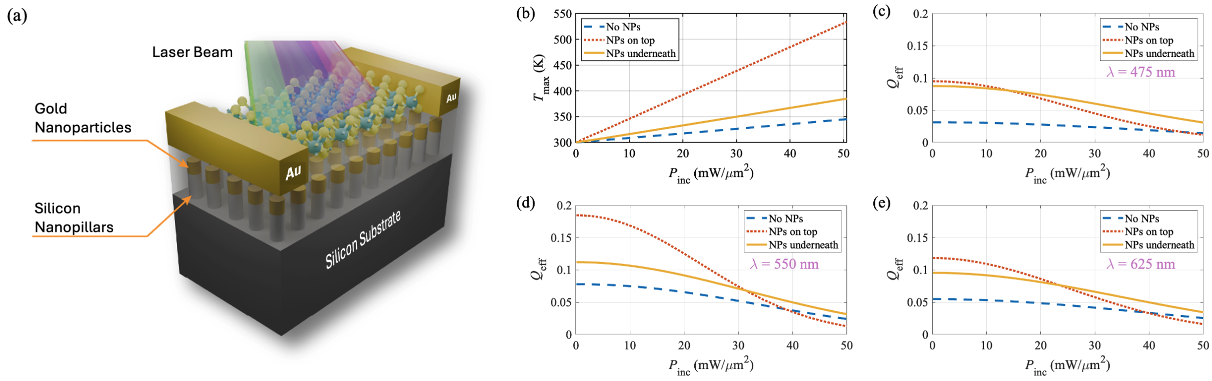

Figure 1: (a) Schematic illustration of an excito-plasmonic phototransistor where NPs are under the monolayer of MoS_2 and on top of silicon nanopillars for more efficient heat dissipation. (b) Maximum temperature for λ = 550 nm and (c)–(e) quantum efficiency for λ = 475, 550, 625 nm, respectively, as a function of input optical power for the phototransistors without NPs (blue dashed curve), with NPs on top (red dotted curve) and NPs underneath (yellow solid curve).

For a proof-of-concept demonstration, we selected monolayer molybdenum disulfide (MoS_2) as our material of choice [4], and we examine the performance variations of 2D material-based bare phototransistors and the ones with NPs placed on top and underneath the MoS_2 layer, as shown in Fig. 1 (a), as functions of incident power and wavelength.

Figure 1 (b) shows the local temperature inside the MoS_2 layer with and without NPs. We observe that the plain phototransistor experiences the weakest heating, and the phototransistor with NPs on top experiences the most substantial heating. In all cases, the induced temperature in monolayer MoS_2 has almost a linear relationship with absorbed power. In Figs. 1 (c)–(e), we plot the quantum efficiency as a function of optical excitation at three wavelengths. We observe that enhancing the local electric field through plasmonic resonances under weak optical excitations leads to increased quantum efficiency. However, as the optical power increases, this field enhancement causes a significant rise in local temperature, ultimately resulting in a substantial drop in the phototransistor’s quantum efficiency. However, placing metal NPs beneath the 2D material and supporting them with silicon nanopillars provides a more efficient heat dissipation mechanism due to the high thermal conductivity of silicon.

[1] R. Islam, I. Anjum, C.R. Menyuk, and E. Simsek, Sci. Rep. **14**, 15269 (2024).
[2] R. Islam, I. Anjum, C.R. Menyuk, and E. Simsek, J. Comput. Electronics **24** (4) (2025).
[3] E. Simsek *et al.*, IEEE Trans. Electron Devices **70** (7), 3643–3648 (2023).
[4] B. Mukherjee *et al.*, Opt. Mater. Express **5** (2), 447–455 (2015).