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Plasmonic enhancement of photocurrent in MoS₂ field-effect-transistor

Jiadan Lin,¹ Hai Li,² Hua Zhang,² and Wei Chen^{1,3,4,a)}

¹Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542

²School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

³Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543

⁴Graphene Research Centre, National University of Singapore, 2 Science Drive 3, Singapore 117542

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The two-dimensional material, molybdenum disulfide (MoS₂), has attracted considerable attention for numerous applications in optoelectronics. Here, we demonstrate a plasmonic enhancement of photocurrent in MoS₂ field-effect-transistor decorated with gold nanoparticles, with significantly enhanced photocurrent peaked at the plasmon resonant wavelength around 540 nm. Our findings offer a possibility to realize wavelength selectable photodetection in MoS₂ based phototransistors.

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In the past few years, intensive research efforts have been devoted to the investigation of two-dimensional (2D) materials, such as graphene and various transition metal chalcogenides.^{1–19} Molybdenum disulfide (MoS₂) is a typical representative of transition metal chalcogenide material family, which consists of S-Mo-S layers bonded by van der Waals interaction.^{4,12,20–22} With reduced number of layers, sizable gap of MoS₂ can be achieved, ranging from the indirect gap of 1.1 eV for bulk²⁰ to the direct gap of about 1.8 eV for monolayer.⁴ Benefiting from the strong absorption in the visible band, MoS₂ has been widely used in photocatalysis²³ and photodetection^{24,25} applications. However, monolayer or few-layer MoS₂ films turn into weak light absorber due to the thickness reduction. To address this issue, we demonstrate a significant plasmonic enhancement of photocurrent of MoS₂ field-effect-transistor by decorating its surface with gold (Au) nanoparticles (NPs). The localized surface plasmon in gold NPs^{26–29} largely improves the light absorption cross section of the MoS₂ layer underneath. It is also found that the gold-NPs decorated MoS₂ transistors possesses a photocurrent response peaked at the plasmon resonant wavelength of around 540 nm.

Figure 1(a) schematically shows the structure of our MoS₂ field-effect-transistor fabricated by the conventional electron beam lithography followed by lift-off process.⁶ In this study, the few-layer MoS₂ samples were mechanically exfoliated (scotch-tap method) from commercially available crystals of molybdenite (SPI supplies) and then transferred onto a SiO₂/Si chip.¹ The thickness of the MoS₂ flakes (4–5 layers) was measured by a combination of optical contrast [Fig. 1(b)]³⁰ and atomic force microscopy measurements. Cr (5 nm)/Au (50 nm) was used as the source and drain electrodes, deposited by thermal evaporation. The inset in Fig. 1(c) shows the scanning electron microscope (SEM) image of the fabricated device with a channel length of 1 μm. The as-fabricated devices were then decorated by dripping and drying a drop of Au NPs (15 nm in diameter) solution. Au NPs were synthesized according to Frens' method.³¹ In a typical

synthesis, 100 ml HAuCl₄ (0.01% wt. in H₂O) was heated for 10 min, followed by adding 3.5 mL of sodium citrate (1% wt. in H₂O) into the solution. The mixture was heated for another 30 min before cooling down to room temperature. The SEM image of gold NPs on MoS₂ surface [Fig. 1(c)] shows a compact arrangement of Au NPs with a uniform diameter of ~15 nm. It is worth noting that the electrical and optical measurements were carried out on the same MoS₂ transistor devices before and after the Au NPs decoration process.

We carried out electrical characterizations of our MoS₂ transistor at room temperature under atmospheric condition. The transfer curves (source drain current vs. gate voltage) for the back-gate MoS₂ transistor are presented in Fig. 2(a), revealing typical n-type semiconducting property. From the data presented in Fig. 2(a), we can estimate the field-effect mobility of MoS₂ transistor based on the following equation:²⁴ $\mu = (L/W)/(\epsilon_0\epsilon_r/d) \times (dI_{ds}/dV_g)/V_{ds}$, where L and W are the channel length and width, respectively (here $L/W = 1 \mu\text{m}/8 \mu\text{m}$), $\epsilon_0 = 8.854 \times 10^{-12} \text{ Fm}^{-1}$, $\epsilon_r = 3.9$ for SiO₂, $d = 300 \text{ nm}$ for the thickness of SiO₂. The value of the charge carrier mobility (μ) is estimated to be $7.5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, in good agreement with previous reports on back gate MoS₂ transistors.⁶ Note that the Cr/Au contacts used in our device are ohmic, as the source-drain current (I_{ds}) depends linearly on the source drain voltage (V_{ds}) [inset of Fig. 2(a)] with the gate voltage varied from 0 to 80 V.

Photocurrent measurements on MoS₂ transistor were performed using 514 nm light source under constant optical power. Figure 2(b) shows the typical current measurement of our MoS₂ device as a function of gate voltage with and without light illumination at fixed source-drain voltage of 200 mV. Obviously, the recorded source-drain current under illumination was raised when compared with that under dark. The electron concentration n can be estimated using the relation $\mu = 1/(nq\rho)$, where ρ is the resistivity of the MoS₂ transistor device.² The calculated value of electron concentration for MoS₂ transistor device under light illumination is $23.8 \times 10^{15} \text{ cm}^{-3}$, which is almost twice of that without light illumination ($12.6 \times 10^{15} \text{ cm}^{-3}$).

Figures 2(c) and 2(d) show the transport characteristics for the same MoS₂ transistor device decorated with Au NPs.

^{a)} Author to whom correspondence should be addressed. Electronic mail: phycw@nus.edu.sg

FIG. 1. (a) Three-dimensional schematic view of the MoS₂ transistor. (b) Optical image of MoS₂ (4–5 layers) deposited on top of 300 nm SiO₂/Si substrate. Scale bar, 20 μm. (c) Scanning electron microscopy image of Au nanoparticles on MoS₂ surface. Scale bar: 100 nm. Inset: Scale bar: 5 μm.

It is found that the Au NPs decoration induced a slight threshold voltage shift towards positive gate voltage, possibly attributed to an uncontrolled doping effect from the H₂O solvent during the NPs decoration process, or the charge carrier (electron) trapping at the interface between MoS₂ and SiO₂ dielectric in the presence of H₂O. Under light illumination, the source-drain current was significantly increased. Obviously, as shown in Figure 2(d) and Table I, the charge carrier concentration of the Au NPs decorated MoS₂ transistor under light illumination was almost one magnitude higher than that under dark condition, i.e., n increased from $4.60 \times 10^{15} \text{ cm}^{-3}$ (dark) to $45.6 \times 10^{15} \text{ cm}^{-3}$ (with light illumination).

FIG. 2. (a) Transfer characteristics ($I-V_g$) for the back-gated MoS₂ transistor. Inset: $I_{ds}-V_{ds}$ curves acquired for V_{bg} values of 80, 60, 40, 20, and 0 V. (b) Typical transfer curves ($I-V_g$) for the same device under light illumination and dark. (c) Transfer characteristics ($I-V_g$) for the same MoS₂ transistor with Au nanoparticles deposited on top. (d) Typical transfer curves ($I-V_g$) for the same device under light illumination and dark with Au nanoparticles deposited on top.

TABLE I. Charge carrier mobility and electron concentration for MoS₂ transistor.

	Without Au NPs		With Au NPs	
	Dark	Under light	Dark	Under light
Charge carrier mobility ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)	7.50	7.60	8.62	10.16
Electron concentration (10^{15} cm^{-3})	12.6	23.8	4.60	45.6

Fig. 3(a) clearly demonstrates the photocurrent enhancement in MoS₂ transistor device decorated with Au NPs under 514 nm light illumination. To verify the plasmonic nature of the photocurrent enhancement, we measured the photocurrents as a function of excitation light wavelengths at constant optical power [Figs. 3(b) and 3(c)]. For the intrinsic MoS₂ device [Fig. 3(b)], the photocurrent remains almost constant with the light wavelength shorter than ~ 660 nm (exceeding bandgap) and drops dramatically for the longer wavelength, clearly revealing the photocurrent generation via the bandgap excitation.^{4,24} In contrast, for the same device decorated with Au NPs [Fig. 3(c)], we observed enhancement of the photocurrent for all the wavelengths shorter than 660 nm. The photocurrent enhancement peaks at ~ 540 nm, in consistent with the ultraviolet-visible (UV-vis) absorption spectrum of 15 nm Au NPs in solution [Fig. 3(d)]. Therefore, we propose that the localized surface plasmon in Au NPs gives rise to the enhancement of local optical field in the vicinity of Au NPs and thus the light absorption of the MoS₂ layer underneath, thereby resulting in the wavelength-dependent photocurrent enhancement of our MoS₂ device.²⁷ Moreover, these individual localized surface plasmon oscillations in neighboring Au NPs can effectively couple together to further enhance the photocurrent.^{32,33} However, our experimental results could not exclude the possibility of the photocurrent

FIG. 3. (a) A comparison of the outputs of device under 514 nm light illumination without and with Au NPs in small gate voltage range (<20 V). (b), (c) Photocurrent of the device as a function of excitation wavelength of the illumination source at constant optical power without and with Au particles, respectively (SD voltage: 200 mV, G voltage: 20 V). (d) UV-vis spectra of Au nano-particles in solution. Inset: A transmission electron microscopy (TEM) image of Au nano-particles (15 nm). Scale bar: 50 nm.

enhancement caused by the injection of the resonantly excited electron in Au NPs^{34,35} to the conduction band of MoS₂.

In conclusion, we have demonstrated that the photocurrent of MoS₂ transistor device can be increased significantly by decorating the MoS₂ sheet with plasmonic Au nanoparticles. Combining the thin MoS₂ sheet with plasmonic Au NPs produces enhanced local optical field, which can contribute to the enhanced absorption of light in the MoS₂ transistor device. In addition, the device shows maximum photocurrent enhancement at the wavelength corresponding to the Au nanoparticle plasmon resonance. Therefore, it is possible to realize MoS₂ based wavelength-selectable photo-detection by tailoring the size and shape of the coupled plasmonic Au or silver nanostructures.

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