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<td>Author(s)</td>
<td>Lin, Jiadan; Li, Hai; Zhang, Hua; Chen, Wei</td>
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Plasmonic enhancement of photocurrent in MoS$_2$ field-effect-transistor

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The two-dimensional material, molybdenum disulfide (MoS$_2$), has attracted considerable attention for numerous applications in optoelectronics. Here, we demonstrate a plasmonic enhancement of photocurrent in MoS$_2$ 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 MoS$_2$ based phototransistors.

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. Molybdenum disulfide (MoS$_2$) is a typical representative of transition metal chalcogenide material family, which consists of S-Mo-S layers bonded by van der Waals interaction. 4 With reduced number of layers, sizable gap of MoS$_2$ can be achieved, ranging from the indirect gap of 1.1 eV for bulk 20 to the direct gap of about 1.8 eV for monolayer. 4 Benefiting from the strong absorption in the visible band, MoS$_2$ has been widely used in photocatalysis and photodetection applications. However, monolayer or few-layer MoS$_2$ films turn into weak light absorber due to the thickness reduction. To address this issue, we demonstrate a significant plasmonic enhancement of photocurrent of MoS$_2$ field-effect-transistor by decorating its surface with gold (Au) nanoparticles (NPs). The localized surface plasmon in gold NPs largely improves the light absorption cross section of the MoS$_2$ layer underneath. It is also found that the gold-NPs decorated MoS$_2$ transistors possesses a photocurrent response peaked at the plasmon resonant wavelength of around 540 nm.

Figure 1(a) schematically shows the structure of our MoS$_2$ field-effect-transistor fabricated by the conventional electron beam lithography followed by lift-off process. In this study, the few-layer MoS$_2$ samples were mechanically exfoliated (scotch-tape method) from commercial available crystals of molybdenite (SPI supplies) and then transferred onto a SiO$_2$/Si chip. 1 The thickness of the MoS$_2$ flakes (4–5 layers) was measured by a combination of optical contrast 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 fabricated devices were then decorated by dipping 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 HAuCl$_4$ (0.01% wt. in H$_2$O) was heated for 10 min, followed by adding 3.5 mL of sodium citrate (1% wt. in H$_2$O) into the solution. The mixture was heated for another 30 min before cooling down to room temperature. The SEM image of gold NPs on MoS$_2$ 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 MoS$_2$ transistor devices before and after the Au NPs decoration process.

We carried out electrical characterizations of our MoS$_2$ transistor at room temperature under atmospheric condition. The transfer curves (source drain current vs. gate voltage) for the back-gate MoS$_2$ 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 MoS$_2$ transistor based on the following equation:

\[ \mu = (L/W) \left( \frac{\sigma_{th}}{\rho} \right) \times \frac{(dV_{ds}/dV_{gs})/V_{ds}}{C_0} \]

where \(L\) and \(W\) are the channel length and width, respectively, \(\sigma_{th}\) is the sheet conductance per unit area, \(\rho\) is the resistivity, \(C_0\) is the capacitance per unit area, \(dV_{ds}/dV_{gs}\) is the transconductance, \(V_{ds}\) is the drain source voltage. The calculated value of electron mobility is 7.5 cm$^2$/Vs, which is almost twice of that reported in previous reports on back gate MoS$_2$ transistors. 6 Note that the Cr/Au contacts used in our device are ohmic, as the source–drain current density (\(J_{ds}\)) depends linearly on the source drain voltage (\(V_{ds}\)).

Figure 2(b) shows the typical current measurement of our MoS$_2$ transistor device as a function of gate voltage with and without light illumination at fixed source–drain voltage of 200 mV. The illuminated source–drain current under illumination was raised when compared with that under dark. The electron concentration \(n\) can be estimated using the relation \(\mu = (1/\rho n&q\), where \(\rho\) is the resistivity of the MoS$_2$ transistor device. 7 The calculated value of electron concentration for MoS$_2$ transistor device under light illumination is 23.8 \times 10^{15} $cm^{-3}$, which is almost twice of that without light illumination (12.6 \times 10^{15} $cm^{-3}$).
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 H$_2$O solvent during the NPs decoration process, or the charge carrier (electron) trapping at the interface between MoS$_2$ and SiO$_2$ dielectric in the presence of H$_2$O. 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 MoS$_2$ transistor under light illumination was almost one magnitude higher than that under dark condition, i.e., $n$ increased from $4.60 \times 10^{15}$ cm$^{-3}$ (dark) to $45.6 \times 10^{15}$ cm$^{-3}$ (with light illumination).

Table I. Charge carrier mobility and electron concentration for MoS$_2$ transistor.

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<th>Without Au NPs</th>
<th>With Au NPs</th>
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<td><strong>Dark</strong></td>
<td><strong>Under light</strong></td>
<td><strong>Dark</strong></td>
</tr>
<tr>
<td>Charge carrier mobility (cm$^2$ V$^{-1}$ s$^{-1}$)</td>
<td>7.50</td>
<td>7.60</td>
</tr>
<tr>
<td>Electron concentration ($10^{15}$ cm$^{-3}$)</td>
<td>12.6</td>
<td>23.8</td>
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Fig. 3(a) clearly demonstrates the photocurrent enhancement in MoS$_2$ 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 MoS$_2$ device [Fig. 3(b)], the photocurrent remains almost constant with the light wavelength shorter than $\sim$660 nm (exceeding bandgap) and drops dramatically for the longer wavelength, clearly revealing the photocurrent generation via the bandgap excitation. 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 $\sim$540 nm, in consistent with the ultraviolet-visible (UV-vis) absorption spectrum of 15 nm Au NPs in solution [Fig. 3(d)]. Therefore, we propose that the localized surface plasmon in Au NPs gives rise to the enhancement of local optical field in the vicinity of Au NPs and thus the light absorption of the MoS$_2$ layer underneath, thereby resulting in the wavelength-dependent photocurrent enhancement of our MoS$_2$ device. Moreover, these individual localized surface plasmon oscillations in neighboring Au NPs can effectively couple together to further enhance the photocurrent. However, our experimental results could not exclude the possibility of the photocurrent...
enhancement caused by the injection of the resonantly excited electron in Au NPs\textsuperscript{34,35} to the conduction band of MoS\textsubscript{2}.

In conclusion, we have demonstrated that the photocurrent of MoS\textsubscript{2} transistor device can be increased significantly by decorating the MoS\textsubscript{2} sheet with plasmonic Au nanoparticles. Combining the thin MoS\textsubscript{2} sheet with plasmonic Au NPs produces enhanced local optical field, which can contribute to the enhanced absorption of light in the MoS\textsubscript{2} 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 MoS\textsubscript{2} based wavelength-selectable photodetection by tailoring the size and shape of the coupled plasmonic Au or silver nanostructures.

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\textsuperscript{5}A. Splendiani, L. Sun, Y. Zhang, T. Li, J. Kim, C.-Y. Chim, G. Galli, and F. Wang, Nano Lett. \textbf{10}, 1271 (2010).


