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Electrical Conduction and Photoconduction in $PtSe_2$ Ultrathin Films †

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Abstract: We report the characterization of back-gated field-effect transistors fabricated using platinum diselenide ($PtSe_2$) ultrathin films as channel. We perform a detailed study of the electrical conduction as well as of the photoconductivity. From the gate modulation of the channel current we obtain the signature of p-type semiconducting conduction with carrier mobility of about 30 $cm^2\ V^{-1}\ s^{-1}$. More interestingly, $PtSe_2$ devices exposed to light, either in air and in vacuum, exhibit a negative photoconductivity, that we explain by a photogating effect due to charge trapping in the gate dielectric and light-induced desorption of adsorbates.

Keywords: $PtSe_2$; field effect transistor; mobility; photoconductivity; negative photoconductivity; photogating effect

1. Introduction

Two-dimensional (2D) transition-metal dichalcogenides (TMDs) have been widely investigated for their interesting properties and applications [1–4]. More recently, TMDs based on group-10 transition metals such as $PdSe_2$ ad $PtSe_2$ have attracted growing attention [5–7]. These materials crystallize in an octahedral lattice structure where the transition metal atoms are coordinated with six chalcogens. The presence of d-electrons in the group-10 transition metals gives rise to additional semiconductor bands making the electrical and optical properties largely tunable by the number of layers [8]. Monolayer $PtSe_2$ has an indirect bandgap of ~1.2 eV, which is expected to reduce to 0.3 eV for the bilayer and vanish for the bulk [9].

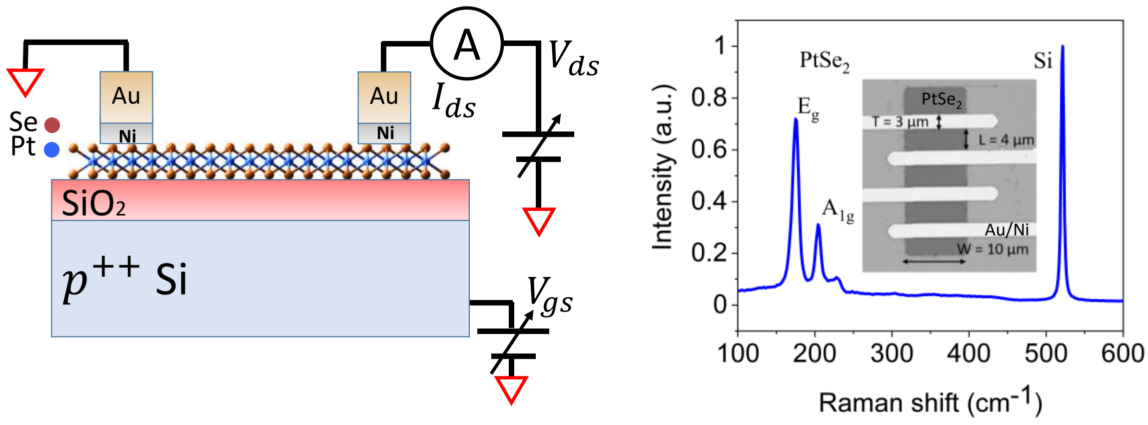
The bandgap of $PtSe_2$ covers the spectral range that is important for telecommunications and solar energy harvesting [10], and the carrier mobility (theoretically predicted up to 4000 $cm^2\ V^{-1}\ s^{-1}$ [11] and experimentally found to be around 200 $cm^2\ V^{-1}\ s^{-1}$ [12]), competitive with black phosphorus, can enable fast electronic devices [13].

In this paper, we study the electrical properties of field-effect transistor realized using 3 nm-thick $PtSe_2$ film. We report semiconducting p-type conduction, and relatively high hole mobility.

Interestingly, we report photoconduction measurements that demonstrates that the $PtSe_2$ devices show negative photoconductivity, which we explain by a photogating effect due to charge trapping in the gate dielectric and light-induced desorption of adsorbates.

2. Experimental Section

$PtSe_2$ film, obtained by direct selenization of 0.7 nm thick Pt film (fabrication details in ref. [14]), is transferred on SiO_2(85 nm)/p-Si substrate and it is etched by SF_6-based inductively coupled plasma process. The patterned $PtSe_2$ (6 layers thick) is then contacted by Ni(20nm)/Au(150 nm) metal leads. A schematic of the $PtSe_2$ FET is shown in Figure 1a.



(**a**) (**b**)

Figure 1. (**a**) Schematic of $PtSe_2$ back gated FET and mesurements configuration; (**b**) Raman characterization of $PtSe_2$ sheet, showing E_g peak at 176 cm^{-1} and A_{1g} peak at 205 cm^{-1}. Inset: SEM image of the device.

In Figure 1b, we show the Raman spectrum for the $PtSe_2$sample, in which we observe the E_g peak at $76\ cm^{-1}$ and the A_{1g} peak at $205\ cm^{-1}$ that give indication of multilayer $PtSe_2$ [15]. In the inset, an SEM image of the device is shown. The transistors were characterized inside a cryogenic Janis ST-500 Probe Station, working at variable temperature and pressure, by connecting the probes to a Keytley 4200 source-measurement unit. The photoconductivity measurements were performed by using a super-continuous white light source (NKT Photonics, Super Compact) with wavelength ranging from 450 nm to 2400 nm and 100 mW/cm^2 maximum intensity.

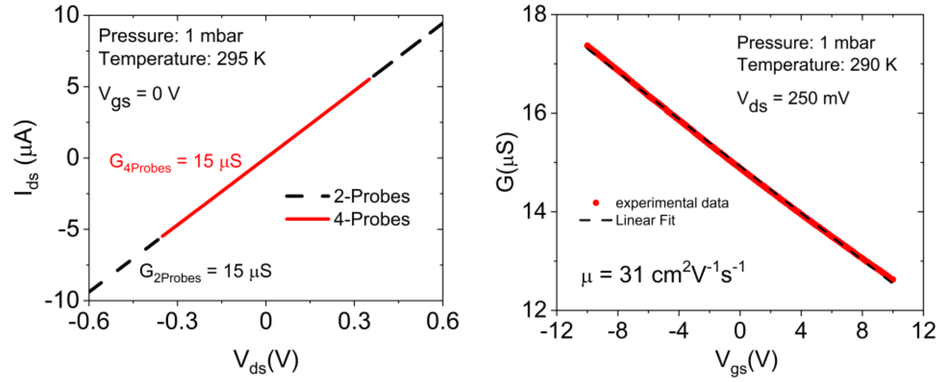
3. Results and Discussion

3.1. Electrical Characterization

We initially applied two- and a four-probe configuration to measure the channel $I_{ds} - V_{ds}$ characteristics. Figure 2a shows that the two techniques yield the same result, indicating that the device has good ohmic contacts with low resistance. Therefore, we decided to use the simplest two-probe setup for further electrical characterization.

Figure 2b, shows an increasing conductance G when the temperature T is raised from 100 K to 400 K revealing the semiconducting nature of the $PtSe_2$ nanosheet. The $G - V_{gs}$ transfer characteristics, where $G = I_{ds}/V_{ds}$ is the channel conductance at fixed drain voltage, reported in Figure 2b confirm the semiconducting nature of the channel and reveals that it has a p-type behavior, as the channel conductance decreases for positively increasing gate voltage. The p-type doping of the $PtSe_2$ channel can be attributed to O_2 adsorbates [6,16–18] as well as to Pt vacancies [19]. Furthermore, the use of Ni as the contact material facilitates hole injection as the Ni Fermi level aligns to the top of the valence band of $PtSe_2$.

We evaluated the field effect mobility as $\mu = \frac{L}{WC_{ox}V_{ds}}\frac{dI_{ds}}{dV_{gs}}$ (I_{ds} and V_{ds} are the drain current and voltage, $C_{ox} = 3.11\ nFcm^{-2}$ is the SiO_2 capacitance per area, L and W are the channel length and width). The value of $31\ cm^2\,V^{-1}\,s^{-1}$ at room temperature is higher than that measured in differently fabricated $PtSe_2$ devices [5,12] or in similar devices with other TMDs such as $PdSe_2$, MoS_2 or WSe_2 [16,20,21].

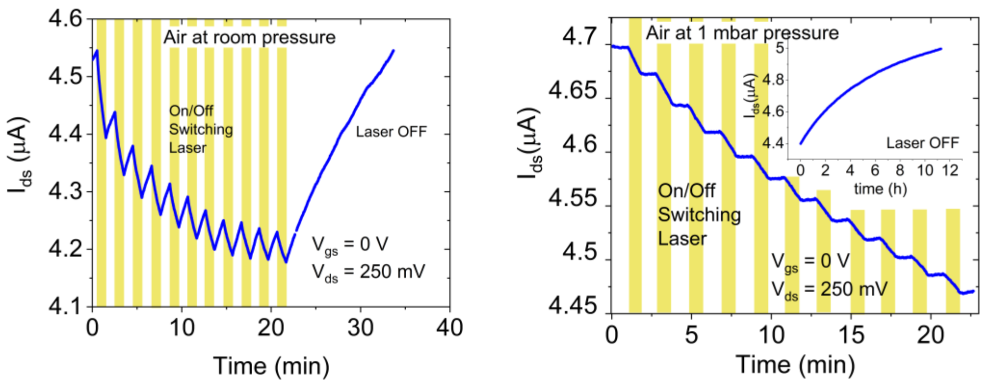


(**a**) (**b**)

Figure 2. (**a**) $I_{ds} - V_{ds}$ output curves measured in two- and four-probe configurations. (**b**) $G - V_{gs}$ transfer curve showing p-type behaviour and field effect mobility of 31 $cm^2\ V^1\ s^{-1}$.

3.2. Photoresponse

The effect of light on $PtSe_2$ nanosheets was investigated by illuminating the device with a supercontinuous white laser (450–2400 nm), with light pulses of given time duration and intensity. Figure 3a,b show the device channel current under fixed bias conditions for switching light at the intensity of 30 mW/cm^2, in air at room pressure and at 1 mbar, respectively.



(**a**) (**b**)

Figure 3. (**a**) I_{ds} drain current subjected to switching light pulses (30 mW/cm^2), monitored in air at room pressure. (**b**) I_{ds} drain current subjected to switching light pulses (30 mW/cm^2), monitored in air at 10^{-3} mbar pressure.

After a sequence of 12 pulses, 2 min long, the laser is switched off and the current is monitored in dark. Surprisingly, each laser pulse provokes a reduction of the current. Such behavior, that is referred to as negative photoconductivity, is opposite to the current increase normally observed under light as an effect of electron-hole (e-h) pair photo-generation [22–24]. We point out that current reduction is a reversible phenomenon as the device returns slowly to the pre-irradiation state when the light source is turned off, with recovery significantly faster in air at room pressure.

The negative photoconductivity could be caused by a photogating effect due to charge trapping in the SiO_2 layer and light-induced oxygen desorption [25,26].

Holes photogenerated in the Si substrate and in the $PtSe_2$ channel can be trapped in the SiO_2 gate dielectric and act as a positive gate that lowers the channel conductance of the p-type transistor. Simultaneously, electrons in O_2 (and perhaps H_2O) molecules adsorbed over the $PtSe_2$ channel can be excited by light into the channel. The neutralized O_2 molecules can be easily desorbed causing a decrease of the channel doping, hence of its conductivity. Both charge trapping and O_2 desorption decrease the current by a mechanism which is reversible with characteristic time depending on hole detrapping and O_2 adsortpion. Obviously oxygen adsorption is facilitated at room pressure, thus explaining the faster recovery in air at room pressure.

4. Conclusions

In conclusion, we investigated the electrical transport in $PtSe_2$ layers used as the channel of back gated field effect transistors. The transistor transfer characteristic indicated p-type conduction with mobility up to $\sim 40\ cm^2\ V^{-1}\ s^{-1}$ at room temperature. Exposure to light showed a dominant photogating effect, due to charge storage in the SiO_2 dielectric and light induced desorption of adsorbates that cause a negative photoconductivity.

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Conflicts of Interest: The authors declare no conflict of interest.

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