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Velocity saturation in few-layer MoS$_2$ transistor

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In this work, we perform an experimental investigation of the saturation velocity in MoS$_2$ transistors. We use a simple analytical formula to reproduce experimental results and to extract the saturation velocity and the critical electric field. Scattering with optical phonons or with remote phonons may represent the main transport-limiting mechanism, leading to saturation velocity comparable to silicon, but much smaller than that obtained in suspended graphene and some III–V semiconductors. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4840175]

Graphene research has shed light on the world of two-dimensional materials, which have recently attracted the interest of the research community, because of their potential to enable and sustain device scaling down to the single-digit nanometer region.

MoS$_2$ is one of these candidates. As a tangible advantage with respect to graphene, MoS$_2$ has a band-gap ranging from 1.3 eV to 1.8 eV, depending on the number of atomic layers,\textsuperscript{1,2} but on the other hand it has a smaller mobility $\mu$ (in single-layer structure of the order of tens of cm$^2$/Vs (Ref. 3)).

Transistors exploiting MoS$_2$ as a channel material have been first experimentally demonstrated in Ref. 4, showing large current modulation, when applying supply voltage scaling suggested by the ITRS.\textsuperscript{5} A theoretical investigation of their limitations and performance has been addressed in Refs. 6 and 7, and an integrated circuit has been demonstrated in Ref. 8, where a MoS$_2$-based NAND-gate and a 5-stage ring oscillator have been fabricated.

However, whether MoS$_2$ can be a promising channel material is an open question, which can be addressed by investigating the figures of merit related to charge transport in nanoscale devices.

In nanoscale MOSFETs, for high longitudinal electric field, the carrier velocity depends linearly on the longitudinal electric field induced by the drain-to-source voltage only for small fields and then reaches a saturation velocity $v_{\text{sat}}$. As a consequence, understanding the $v_{\text{sat}}$ of new materials is of the utmost importance, in order to predict the drain current achievable in operating conditions.

In this work, we extract $v_{\text{sat}}$ in FETs with MoS$_2$ channel, at different temperatures (300–500 K) from purposely fabricated devices. The extracted values show that velocity saturation in MoS$_2$ is comparable to what obtained in silicon, but almost an order of magnitude smaller as compared to graphene and some III–V materials.

The fabrication procedure is based on the processes used for graphene field-effect transistors.\textsuperscript{9} The fabricated device is a backgated MoS$_2$ field-effect transistor, with channel length $L = 1 \mu$m and channel width $W = 1.2 \mu$m. The MoS$_2$ layer consists of three atomic layers. We have used highly p-doped Si wafers covered with a 90 nm layer of thermally grown SiO$_2$ used as a substrate. Subsequently, the MoS$_2$ layer has been exfoliated with adhesive tape from a natural crystal and deposited on the substrate. Few-layer MoS$_2$ flakes have been identified using optical microscopy and contrast determination of the MoS$_2$ relative to the substrate, with a procedure similar to the one known for graphene flakes.\textsuperscript{10} After the identification of a flake, the contact electrodes have been fabricated by photolithography, sputter deposition of 40 nm layer of nickel, and a subsequent lift-off process. As we have not observed a channel length dependence of the field effect mobility for devices with channel length ranging from 1 to 8 $\mu$m, we can assume a negligible contribution of the contact resistance to the total resistance of our devices. Finally, 44 nm of Al$_2$O$_3$ were grown on top of the device using atomic layer deposition. Fig. 1(a) shows the micrograph of a fabricated MoS$_2$ FET.

![Micrograph of a MoS$_2$ FET](Image)

**FIG. 1.** (a) Micrograph of a MoS$_2$ FET. The device is covered with an Al$_2$O$_3$ layer for passivation. The contrast of the MoS$_2$ was increased with respect to the surrounding substrate. (b) Schematic longitudinal cross-section of the fabricated device.
The device structure is depicted in Fig. 1(b). The samples were measured in a needle probe station at temperature from 294 to 473 K. For the electrical characterization an HP 4156 semiconductor parameter analyzer was used.

We have used the analytical model proposed in Ref. 11 to extract the saturation velocity $v_{sat}$. In particular, the drain-to-source current ($I_{DS}$) can be expressed as a function of the channel width and length $W$ and $L$, respectively, the gate capacitance $C_{ox}$, the threshold voltage $V_T$, and the mobility $\mu$ as

$$I_{DS} = \frac{W}{L} \frac{\mu C_{ox} (V_{GS} - V_T)}{1 + \left(\frac{V_{DS} \mu}{L v_{sat}}\right)^{1/a}} \sqrt{V_{DS}}$$  \hspace{1cm} (1)$$

where $V_{GS}$ and $V_{DS}$ are the gate-to-source and drain-to-source voltages, respectively, and $a$ has been taken equal to 1.8 — as in Ref. 11 — for all the considered temperatures.

The mobility is extracted directly from experiments in the linear region as

$$\mu = \frac{L g_m}{W V_{DS} C_{ox}}$$ \hspace{1cm} (2)$$

where $g_m$ is the differential transconductance.

Contact resistance has been neglected in Eq. (1), in agreement with experimental observation.

We obtain $v_{sat}$ as a fitting parameter with measured DC characteristics, through a least mean square procedure. In Fig. 2(a), we show the experimental (solid lines) output characteristics at room temperature, for $V_{GS}$ ranging from 20 to 34 V, in steps of 1 V. As can be observed, current in the saturation region depends linearly on $V_{GS}$, which is a signature of the saturation velocity regime.

In the same picture, we show (dots) the output characteristics given by Eq. (1). The simple analytical model well manages to reproduce the experimental results both in the triode and in the saturation region. In Fig. 2(b), we plot the experimental mobility in the linear region (for $V_{DS} = 0.4$ V) as a function of the charge density in the channel: mobility is almost constant for the considered charge densities and the obtained values are in agreement with mobility in state-of-the-art MoS$_2$ Field-Effect Transistors.

In Fig. 3, the transfer characteristics both in the logarithmic and linear scale are shown. In Fig. 3(b) we show both experimental transfer characteristics (solid lines) above threshold with the model provided by Eq. (1): results are in good agreement. From the transfer characteristics we can

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extract both the sub-threshold swing $SS = 850 \text{ mV/dec}$ and $I_{on}/I_{off} \approx 10^5$.

In Fig. 4(a), mobility is plotted as a function of temperature. Mobility is proportional to $1/T^3$. This dependence can be due either to the dominance of electron-optical phonon coupling (behavior $1/T^{2.6}$ as theoretically demonstrated in Ref. 12) and shown in Ref. 13 or to remote phonons ($1/T^{3.42}$) as experimentally demonstrated in Ref. 14. As expected, this dependence is considerably larger than that foreseen by Density Functional Theory (DFT) calculations in monolayer MoS$_2$. In Table I, the relatively high temperature range considered in our study.

Typical known models for velocity saturation, based on the energy balance model or on the electron temperature model, predict a much weaker dependence on temperature, with exponent ranging from $-0.5$ to $-1.5$.

One possible reason for the much stronger experimental dependence of $v_{sat}$ on temperature could be the role of thermal activation in transport, which certainly is relevant, also in the relatively high temperature range considered in our study. Indeed, in Table I, we show the extracted threshold voltage and the critical electric field $\xi_{cr} \equiv v_{sat}/\mu$ at different temperatures: $V_T$ exhibits a strong dependence on temperature in the considered temperature range, which has been also observed in Ref. 3 and also in that case explained with thermally activated transport. Complete understanding of $v_{sat}$ dependence on temperature surely deserves further investigation.

In Table II we compare the critical electric field $\xi_{cr}$ and $v_{sat}$ of different materials at room temperature. We can observe that $v_{sat}$ and $\xi_{cr}$ in MoS$_2$ are similar to those of more common semiconductors, and almost one order of magnitude smaller than those of suspended graphene and III–V materials.

Another device with $L = 1 \text{ m} \mu$ has also been measured, giving a $v_{sat}$ close to the one shown in Table II (i.e., $v_{sat} = 0.27 \times 10^7 \text{ cm/s}$).

We have extracted the carrier saturation velocity in few-layer MoS$_2$ MOSFETs both in the linear region and in the saturation region of the DC current-voltage characteristics. The strong temperature dependence of $v_{sat}$ and $V_T$ in the 300–500 K temperature range considered reveals the role played by thermally activated transport. We show that the experimental mobility has a temperature dependence close to $T^{-3}$ compatible with scattering with optical or remote phonons. Complete understanding of the temperature dependence of $v_{sat}$ requires additional investigation. Our results confirm that MoS$_2$ can be a promising material for electronics: both $v_{sat}$ and $\xi_{cr}$ are comparable to those of common semiconductors, but few-layer MoS$_2$ has the advantage of being a two-dimensional material, suitable for the realization of few-nm FETs with very good electrostatics. With respect to suspended graphene, both $v_{sat}$ and $\xi_{cr}$ are one order of magnitude lower, but MoS$_2$ has an adequate energy gap for applications in electronics, even at relatively high temperature.

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TABLE I. Threshold voltage ($V_T$) and critical electric field $\xi_{cr}$ (Refs. 17 and 18) at room temperature for different materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>$v_{sat}$ (10$^7$ cm/s)</th>
<th>$\xi_{cr}$ (V/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoS$_2$</td>
<td>0.28</td>
<td>1.15 x $10^5$</td>
</tr>
<tr>
<td>Si</td>
<td>1.02</td>
<td>4 x $10^4$</td>
</tr>
<tr>
<td>Graphene</td>
<td>5.5</td>
<td>10$^5$</td>
</tr>
<tr>
<td>InSb</td>
<td>5</td>
<td>10$^5$</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.72</td>
<td>0.3 x $10^4$</td>
</tr>
<tr>
<td>Ge</td>
<td>0.72</td>
<td>4 x $10^4$</td>
</tr>
<tr>
<td>AlAs</td>
<td>0.85</td>
<td>10$^5$</td>
</tr>
<tr>
<td>GaP</td>
<td>0.88</td>
<td>2 x $10^5$</td>
</tr>
<tr>
<td>GaN</td>
<td>1.4</td>
<td>...</td>
</tr>
<tr>
<td>InGaAs</td>
<td>1.8</td>
<td>...</td>
</tr>
</tbody>
</table>