Monolayer transition metal dichalcogenide based field-effect transistors

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A great deal of interest in two-dimensional materials analogues of graphene has appeared among the scientific community since the demonstration of isolated 2D atomic plane crystals from bulk crystals [1]. Dimensionality is key for the definition of material properties and the same chemical compound can exhibit dramatically different properties depending on whether it is arranged in dots (0D), wires (1D), sheets (2D) or bulk (3D) crystal structure. Notably, experimental studies of 2D atomic crystals were lacking until recently because of the difficulty in their identification [1]. Representative of this class are the 2D monolayer of transition metal dichalcogenides (TMD) with a chemical formula MX_2, where M stands for a transition metal and X for Se, S, or Te. The potential of this family of layered materials for flexible electronics was proposed by Podzorov et al., who demonstrate an ambipolar WSe_2 p-FET with a hole mobility comparable to silicon (~500 cm^2/V-s) [2]. The electronic properties of TMDs vary from semiconducting (e.g., WSe_2) to superconducting (e.g., $NbSe_2$). The semiconducting monolayer TMDs, like MoS_2, $MoSe_2$, $MoTe_2$, WS_2, and WSe_2 are predicted to exhibit a direct gap in the range of 1–2 eV [3]. The wide gap together with a promising ability to scale to short gate lengths because of the optimum electrostatic control of the channel, by virtue of its thinness, make monolayer TMDs very promising for low power switching and optoelectronics applications. The first 2D crystal based FET relying on a semiconducting analogue of graphene was demonstrated using a monolayer MoS2 as the active channel [4]. Low power switching with an I_{ON}/I_{OFF}~10^8 and subthreshold swing (SS) of 74 mV/decade at room temperature, was experimentally measured. More recently, a monolayer p-type WSe_2 FET with an optimum SS ~ 60 mV/decade and I_{ON}/I_{OFF} >10^6 was demonstrated [5].

To boost the development of 2D-material based transistor technology, modeling of the electrical characteristics is essential to cover aspects as device design optimization, projection of performances, and exploration of low-power switching circuits. Some models aimed to explore the performance limits of monolayer TMD transistors have been reported assuming ballistic transport. However, the behavior of state-of-the art devices is far from ballistic and a drift-diffusion transport regime seems more appropriate for channel lengths well above the carrier mean free path. In this context, I propose a model for the current-voltage (I-V) characteristics of monolayer TMD FETs, based on the drift-diffusion theory. As a previous step a surface potential model, accounting for the 2D density-of-states (DOS_{2D}) of monolayer TMDs, is proposed. I will consider that carriers are free to move parallel to the TMD sheet. However their motion is restricted in the perpendicular direction because the strong quantum confinement. The DOS_{2D} has a profound impact on the quantum capacitance, which is essentially different from that of a nanowire (1D) or a bulk (3D) material. Analytical expressions are derived for both the surface potential and drain current covering both subthreshold and above threshold operation regions. The model has been assessed by means of experimental data (Fig. 1) and used to make some predictions on the existing tradeoff between the ON-current and ON/OFF current ratio.

References

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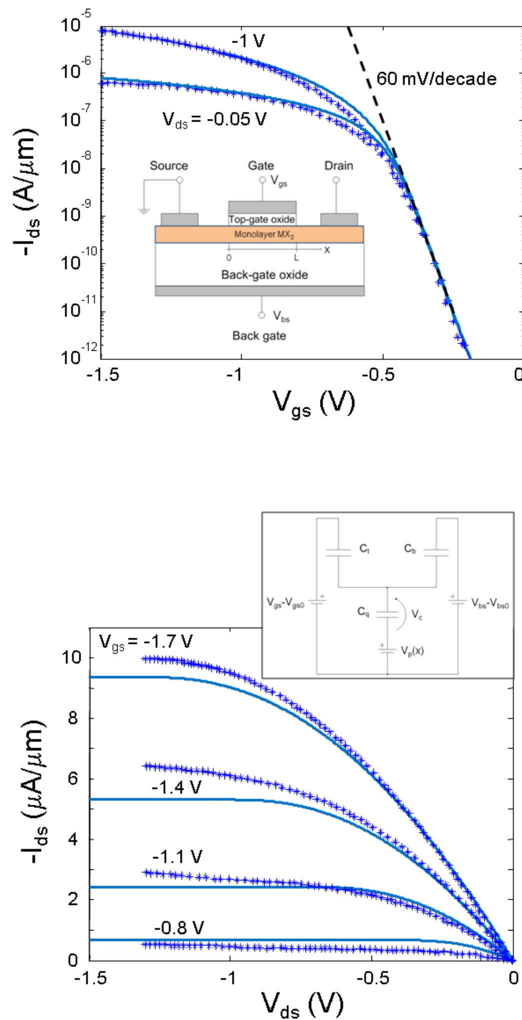

Figure 1. Transfer (a) and output (b) characteristics obtained from the analytical model (solid lines) compared with experimental results from Ref. [5] (symbols). Inset (a): cross section of the dual-gate monolayer TMD transistor. Inset (b): equivalent capacitive circuit.