2D MOSFET operation of a fully-depleted bulk MoS$_2$ at quasi-flatband back-gate

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In this paper, 2D MOSFET operation of a fully-depleted double-gate bulk MoS$_2$ is studied at a quasi-flatband of the back-gate for the first time. Several key device parameters such as equivalent oxide thickness (EOT), carrier concentration, flatband voltage, dielectric constant and carrier mobility were extracted from I-V and C-V characteristics and at room temperature. In a similar operation to the inversion-mode SOI MOSFETs in [1], the backgate was used to keep a sheet of mobile charges on the flake back-side by its quasi-flatband operation at a fixed voltage (0 V). Afterward, the top-gate was used as the active gate to perform mobile charge accumulation or depletion in the channel. Fig. 1 shows the device architecture together with the high frequency R-C equivalent circuit model for this underlap gate architecture. Fig. 2 represents the top-view microscope picture of the fabricated MoS$_2$ bulk MOSFET with a flake thickness of 38 nm, measured by AFM. The fabrication steps include mechanical exfoliation of MoS$_2$ crystals on a 260 nm thick oxidized Si substrate, e-beam lithography to make S/D pads, 50 nm Ni by thermal evaporation and lift-off, gate patterning, high-k/metal-gate stack deposition (1 nm of SiO$_2$ by thermal evaporation, 11 nm of ZrO$_2$ by ALD deposition at 105 °C, 30 nm of Sn by thermal evaporation) and lift-off. The measurements were done at room temperature using an Agilent B1500A Semiconductor Parameter Analyzer. Fig. 3 shows its $\text{I}_d$-$\text{V}_g$ reporting a subthreshold slope of 110 mV/dec. and $\text{I}_{on}$/\$\text{I}_{off}$ of $\sim 1 \times 10^5$, both at $V_{dd}=100$ mV.

EOT, dielectric constant, flatband voltage: Fig. 4 depicts the $C_{ox}$-$\text{V}_g$ measurement between the top-gate and the source-drain electrodes ($V_{dd}=0$ V) at a high frequency regime (1 MHz). In strong accumulation, the EOT numeric value of the gate stack can be extracted from the maximum value of gate-channel capacitance, resulting an EOT value of 6.3 nm. In the partial depletion regime, between threshold and flatband, the gate-channel capacitance would vary by $1/C_{ox}^2 = 1/C_{ox}^2 + 2/(q, \varepsilon_0, \varepsilon_r, \Phi_{bd}, (V_{gs}-V_{th}))$ [2]. The flatband voltage can be extracted from the x-intercept of $1/C_{ox}^2 - 1/C_{ox}^2$, reporting a flatband voltage of -0.45 V. The dielectric constant of the flake can be extracted from the difference in the gate-channel capacitance in strong accumulation and at the threshold voltage (-1.1 V, estimated from the linear onset of $\text{I}_d$-$\text{V}_g$ in Fig. 3), reporting a numeric value of 7.8. This is almost in the range of the reported experimental dielectric constant numeric values in [3].

Carrier concentration: The carrier concentration can be extracted from the slope of $1/C_{ox}^2 - 1/C_{ox}^2$ in the linear region between threshold and flatband, reporting a value of $2.1 \times 10^{17}$ cm$^{-3}$. Note that this method can be applied to the devices with a flake thickness higher than the Debye length (~7.2 nm at this carrier concentration or doping regime).

Series resistance: The series resistance, similar to an inversion-mode MOSFET in [4], can be extracted from the y-intercept of $R_{on}=V_{dd}/I_d$ vs. 1/(V$_{gs}$-V$_{th}$) in linear accumulation regime (V$_{dd}$<V$_{gs}$-V$_{th}$), see Fig. 4, assuming accumulation as the dominant conduction mechanism in comparison to bulk conduction. This assumption is justified considering the channel accumulation conductance ($\mu \cdot C_{ox}.W/L.(V_{gs}-V_{th})$) of three times higher than the bulk conduction at flatband (q, $\varepsilon_0$, $\varepsilon_r$, $\Phi_{bd}$/W/L). An almost similar mobility assumption for bulk and accumulation conduction results a bias range of V$_{gs}$-V$_{th}$$>$0.60 V. A series resistance of 434 kΩ is extracted in Fig. 4, while this fairy high value is due to the used underlap gate design to minimize the parasitic gate-source and drain capacitances. Note that Benzyl Viologen (BV) [5] or SiN$_x$ [6] doping can be performed in the S/D extensions to suppress such resistances as well as minimize their gate-bias-dependencies especially above flatband and for shorter lengths [7].

Carrier mobility: The effective carrier mobility can be extracted using the split C-V method, similar to a junctionless/accumulation-mode device in [8]-[9], covering a wide gate voltage range from threshold to strong accumulation ($\mu_{eff}=W/L/(Q_w-q, V_{dd})$; $Q_w=\int_{V_{th}}^{V_g} C_{gc}.dV_{gs}$). $Q_w$ is the normalized mobile negative charges in the channel per unit area. Fig. 5 shows the numeric effective mobility values after the series resistance correction, reporting a maximum effective electron mobility value of 48 cm$^2$/V.s. For comparison, the effective mobility is also extracted from I-V characteristics, after a series resistance correction and from the $g_{mn}$ values in linear accumulation regime, $\mu_{eff}=g_{mn}/(C_{ox}.W/L.V_{dd})$, reporting a maximum numeric value of 26 cm$^2$/V.s. The slight effective mobility underestimation using only I-V characteristics can be due to neglecting the bias-dependency of the gate-channel capacitance in strong accumulation regime.

Conclusion and further works: In this work, we extracted several device parameters in a double-gate bulk MoS$_2$ MOSFET using C-V and I-V characteristics. Such device extraction methodologies were done assuming a typical linear operation of an accumulation-mode MOSFET from depletion to accumulation. This parameter extraction platform can be used to investigate the possible bias-dependency of key material parameters e.g. dielectric constant and bandgap [10], in a high normal electric field considering a back-gate operation. This includes incorporation of photoluminescence measurement on direct bandgap 2D devices, monolayer e.g. MoS$_2$ and bulk e.g. ReS$_2$ [11] as well as further experiments on the effect of back-gate field on the device performance. The results of these experiments will be reported in a future publication.  

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as additional measurement methods e.g. Hall for comparison of e.g. mobility and carrier concentration values. This work was supported by ATMI Inc. within the i-Rice program.