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Improvement in top-gate MoS₂ transistor performance due to high quality backside Al₂O₃ layer

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A high quality Al₂O₃ layer is developed to achieve high performance in top-gate MoS₂ transistors. Compared with top-gate MoS₂ field effect transistors on a SiO₂ layer, the intrinsic mobility and subthreshold slope were greatly improved in high-k backside layer devices. A forming gas anneal is found to enhance device performance due to a reduction in the charge trap density of the backside dielectric. The major improvements in device performance are ascribed to the forming gas anneal and the high-k dielectric screening effect of the backside Al₂O₃ layer. Top-gate devices built upon these stacks exhibit a near-ideal subthreshold slope of ~69 mV/dec and a high Y-Function extracted intrinsic carrier mobility (μ_0) of 145 cm²/V·s, indicating a positive influence on top-gate device performance even without any backside bias. *Published by AIP Publishing.*

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Transition metal dichalcogenides (TMDs) are at the forefront of research as possible semiconductor channels in low-power, high-mobility devices.^{1–4} Molybdenum disulfide (MoS₂), one of the most studied TMDs, is an attractive 2D material with a thickness dependent band gap that has shown high device performance in a traditional top-gate field effect transistor (FET) structure.^{5–7} Previous studies have shown high on/off ratios (~10⁸), high mobility values (>200 cm²/Vs), and low subthreshold swing (~74 mV/dec) for top-gate MoS₂ devices, typically on SiO₂.⁸ The utilization of SiO₂ is often due to exfoliated MoS₂ having a high optical contrast on SiO₂ dielectric, allowing for quicker and easier detection of flakes. Recent studies have demonstrated the effects of high-k dielectrics on back-gated transistors with improvements in device performance attributed to the dielectric screening effect.^{9–11} However, a dearth of quality capacitance data to ensure a high-quality dielectric has been reported, which oftentimes can result in extraction of improper mobility values due to a high capacitance. Some studies also prefer a dual gate structure, while others have suggested that there is an advantage to sweeping only the back gate due to improper assumptions about top gate capacitance, which has stirred much debate.^{12–14} The top gate capacitance is generally assumed to be between the active device channel and the gate over channel area, resulting in appropriate mobility extraction. This study demonstrates the effect of a high quality annealed Al₂O₃ backside layer for top gate transistors where the I_{ON}/I_{OFF} ratio is ~10⁶, the field effect mobility is ~33 cm²/Vs, and the subthreshold slope (SS) is ~69 mV/dec, without any back gate bias.

Al₂O₃ (~15 nm) dielectric films were deposited on p-Si wafers by atomic layer deposition (ALD). Metal-oxide-semiconductor capacitors (Metal-Al₂O₃-Si) were fabricated to provide a proper understanding of the quality of these films. By photolithography, top electrodes (Cr/Au, 20/150 nm)

with various areas were fabricated with a lift-off process. A forming gas (“FG”:5%H₂/95%N₂) anneal at 400 °C at 1 bar was performed to establish the anneal impact on interface traps,¹⁵ and Al (150 nm) was deposited on the back of the wafer to reduce the series resistance. For the MoS₂ field effect transistors (FETs), scotch tape was used to mechanically exfoliate untreated MoS₂ on top of Al₂O₃. By photolithography, the source/drain was defined on a few layer MoS₂ flake, and then, Cr/Au (20 nm/150 nm) was deposited by thermal evaporation under high-vacuum (10⁻⁶ mbar), followed by a lift-off process. This back-gate device was then FG annealed with pre- and post-anneal I-V measurements. After the post-anneal measurements, 15 min of *in-situ* UV-ozone functionalization treatment was performed, and then, 4 nm of HfO₂ was deposited at 200 °C using an ALD tetrakis-ethylmethylamino hafnium (TEMA-Hf)/H₂O process.¹⁶ The combination of the FG anneal and the UV/O₃ functionalization of the MoS₂ surface is anticipated to reduce residual, process-induced contamination from lithography prior to gate dielectric formation.^{16–18} The final step involved the high-vacuum deposition of a Cr/Au top gate using the same process as the source/drain, converting the back-gate device into a top-gate 3-terminal FET. The same fabrication flow was used on devices with a SiO₂ backside layer for proper device comparison.

From frequency dependent C-V measurements of Al₂O₃ MOSCAPs [Figs. 1(a) and 1(b)] ranging from 500 Hz to 1 MHz, we were able to determine the optimum annealing temperature to achieve low frequency dispersion in the depletion region, typically attributed to interface traps (Q_{it}), and in the accumulation region, typically attributed to the series resistance (R_s), with the former being the most impacted by the FG annealing. First, FG anneals at 200 °C, 300 °C, and 400 °C were performed with C-V measurements done after each anneal. Interface trap density (D_{it}) extraction [Fig. 1(c)] using the High-Low Frequency method (see

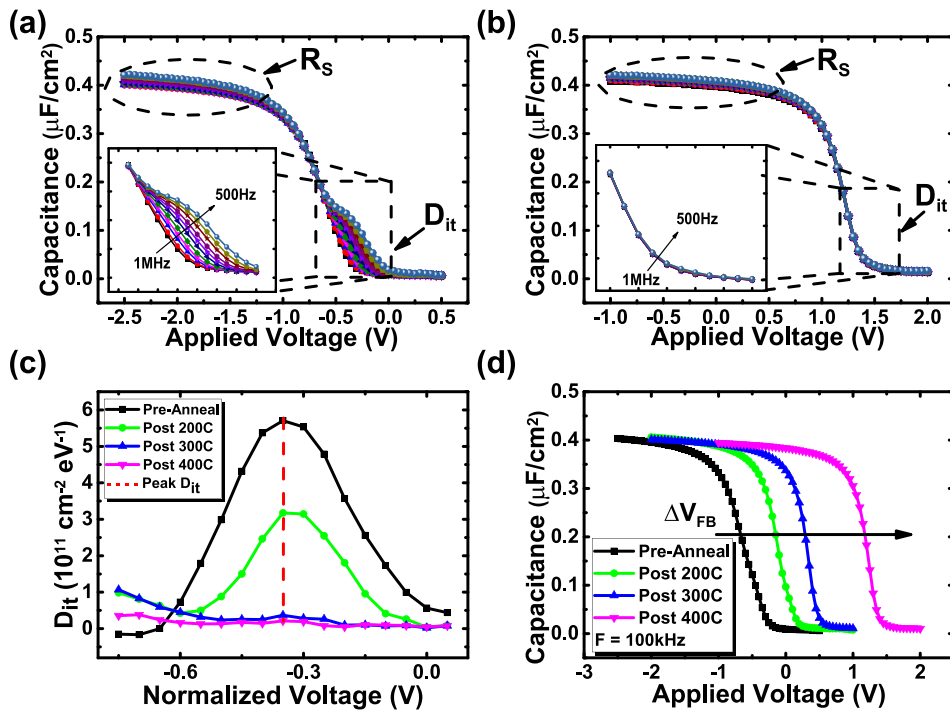


FIG. 1. (a) Frequency dependent C-V before annealing with evidence of high dispersion and (b) frequency dependent C-V post 400°C FG anneal with a significant reduction in dispersion. (c) High-low frequency interface trap density (D_{it}) extraction for a range of subsequent anneal temperatures and (d) the flat-band voltage shift accompanying each subsequent anneal.

supplementary material),¹⁹ a technique well suited for MOS capacitors, shows a significant reduction from the peak D_{it} of $5.7 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ of pre-annealed Al_2O_3 to an extremely low D_{it} of $2 \times 10^{10} \text{ cm}^{-2} \text{ eV}^{-1}$ post 400°C anneal. The flat-band voltage shift (ΔV_{FB}), typically attributed to a reduction of fixed oxide charges (Q_f), post anneal [Fig. 1(d)] was another indicator of optimal annealing temperature as any subsequent anneals after 400°C did not yield any further shift. While some recent publications claim to have good dielectric properties, the associated C-V data indicate high frequency dispersion¹¹ and/or D_{it} extraction using widely critiqued methods.^{20,21} These discrepancies can lead to improper extraction of device parameters and especially an overestimation of field effect mobility.

With a high quality Al_2O_3 backside dielectric layer, back-gate devices with an MoS_2 channel can be used to demonstrate the effect of the FG anneal in terms of device performance. Several back-gate FETs were thus fabricated on a high-k backside layer in order to study the effect of the FG anneal. While the MoS_2 flakes were untreated and therefore had sulfur vacancies, among other likely defects and impurities,^{22,23} the thickness of each flake was $\sim 4\text{--}5 \text{ nm}$, approximated using the optical interference contrast method, in order to keep the variability low. The I-V characteristics of the devices were measured pre- and post-anneal at 400°C, with the statistics (8 back-gate FETs) of the I_{ON}/I_{OFF} ratio and SS_{MIN} shown in Fig. 2(a). A favorable trend is shown with an increase in I_{ON}/I_{OFF} and a decrease in SS_{MIN} attributed to the beneficial effects of the anneal on the Al_2O_3 layer. With an average I_{ON}/I_{OFF} ratio of $\sim 10^3$ and SS_{MIN} of $\sim 270 \text{ mV/dec}$ pre-anneal, the devices' performance greatly improved with an average I_{ON}/I_{OFF} ratio of $\sim 10^6$ and SS_{MIN} of $\sim 117 \text{ mV/dec}$ post-anneal. This increase in performance can be attributed to not only passivation but also a potential reduction in impurities at the backside $\text{MoS}_2/\text{Al}_2\text{O}_3$ interface. In Fig. 2(b), $I_D\text{-}V_D$ indicates a non-linear behavior pre-

anneal and more linear behavior post-anneal, suggesting that annealing also has a beneficial effect on the contacts, not just the dielectric, potentially removing the need for sulfur passivation treatments.^{24–26} It is noted that with back-gate devices, proper C_{OX} extraction from C-V measurements is nearly impossible due to the high capacitance resulting from the

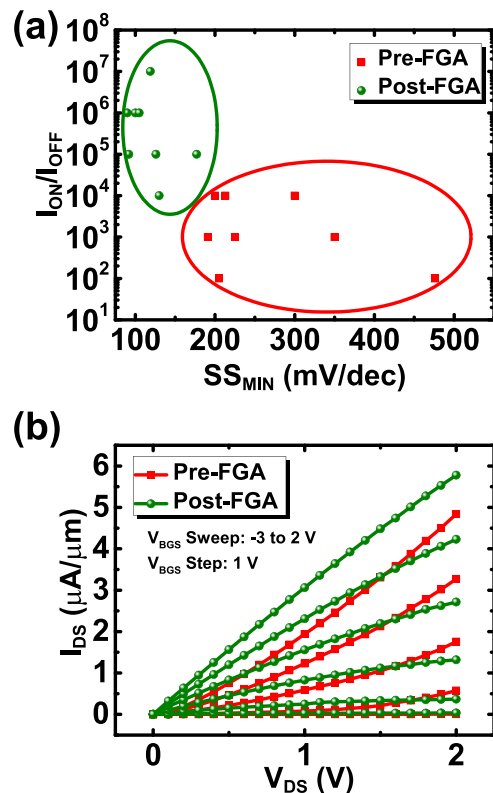


FIG. 2. (a) Statistics of back-gated FETs pre- and post-FG anneal in terms I_{ON}/I_{OFF} and SS_{min} , demonstrating a beneficial trend in device performance as a result of an effect of the anneal on the high-k backside layer for a total of 8 devices. (b) $I_D\text{-}V_D$ pre-FG anneal and post-FG anneal shows a beneficial effect on the contacts with a conversion from non-linear to linear curves.

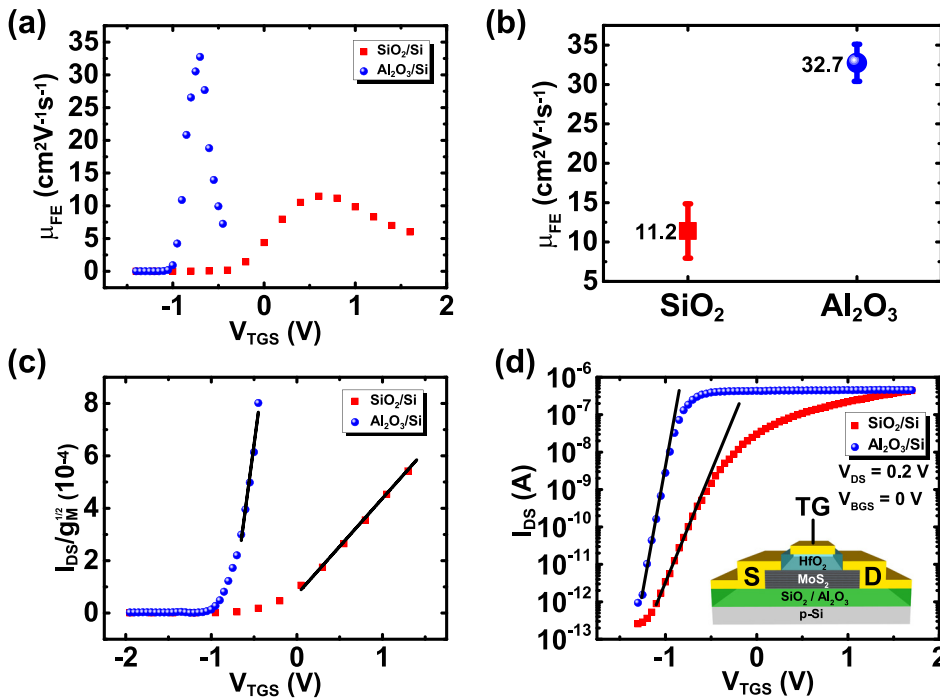


FIG. 3. (a) Field effect mobility comparison between a top-gate FET on a pre-annealed Al₂O₃ layer and an SiO₂ layer with the (b) mobility statistics for the 4 best top-gate FET devices for each Al₂O₃ and SiO₂ backside layer. (c) Y-Function extraction for top-gate devices on Al₂O₃ and SiO₂ with (d) I_{DS} - V_{TGS} characteristics of devices on Al₂O₃ and SiO₂, demonstrating an increase in mobility and a decrease in SS due to a high-k backside layer with the inset showing a cross-section of a top-gate structure.

large area of the source/drain pads that dwarf the MoS₂ gate channel capacitance, nor would it be appropriate to extract D_{it} using the subthreshold slope expression due to the uncertainty in C_{OX} and C_{bulk} .^{19,27} With parameters such as the field effect mobility (μ_{FE}) reliant on C_{OX} for proper extraction, the proper device evaluation of the back-gate FET is limited, especially since its applicability to current CMOS technology is essentially non-existent. In order to properly compare the effect of the Al₂O₃ backside layer on device performance, a top-gate FET structure is needed.

Conversion from a back-gate to a top-gate device structure allows continuous evaluation of the same MoS₂ channel,²⁸ especially if it demonstrates high device performance as a back-gate device. With the backside dielectric layer already exposed to a 400 °C FG anneal, a top-gate HfO₂ dielectric was deposited after the MoS₂ flake was treated using a UV-ozone functionalization treatment and a top-gate (Cr/Au) was deposited under high-vacuum thereafter. Top-gated devices on a SiO₂ layer went through the same process, and two comparable devices were chosen for characterization. In Fig. 3(a), the field effect mobility extraction (see [supplementary material](#)) for each top-gate device with a peak μ_{FE} of ~ 11 cm² V⁻¹ s⁻¹ for the device on the SiO₂ layer and a peak μ_{FE} of ~ 33 cm² V⁻¹ s⁻¹ for the device on the Al₂O₃ layer shows $\sim 3\times$ improvement in mobility. Mobility statistics for several top-gate devices [(Fig. 3(b)) demonstrates a similar trend across multiple devices (4 for each backside layer). This indicates that even without any backside bias, the dielectric layer upon which the top-gate device rests has an effect on its overall performance.

In order to compensate for the contact resistance, the extraction of intrinsic carrier mobility, as well as the contact resistance and threshold voltage, using the Y-Function Method (see [supplementary material](#)) in Fig. 3(c) can be reliably used.^{29,30} The extracted parameters of the contact resistance (R_C) for top-gate devices on SiO₂ and Al₂O₃ layers are

~ 28 k $\Omega\cdot\mu\text{m}$ and ~ 24 k $\Omega\cdot\mu\text{m}$, respectively. This may account for the low drive current of both devices, suggesting that lowering R_C may be able to further enhance the device performance.³¹ The intrinsic mobilities (μ_0) for the device with SiO₂ and Al₂O₃ layers are 38 cm² V⁻¹ s⁻¹ and 145 cm² V⁻¹ s⁻¹, respectively, which is $4\times$ higher due to a high-k backside layer.³² With the observation of the device performance enhancement, these results suggest that there is an advantage in using backside dielectrics for 2D materials other than the traditional SiO₂. The subthreshold slope (SS) also shows a major improvement with an SS_{MIN} of ~ 154 mV/dec for a device on a SiO₂ layer and a near-ideal SS_{MIN} of ~ 69 mV/dec, a record high, for a device on a high quality Al₂O₃ layer. This indicates that a good choice of a backside dielectric layer for top-gate MoS₂ FETs can provide high device performance without any backside bias. Further improvement depends on the quality of the MoS₂ flakes/channel, as a reduction in defects and impurities would also yield a better channel for a device.³³

A highly robust Al₂O₃ back-gate layer for high-k top-gate MoS₂ FETs has substantially improved device performance. We were able to reduce the interface trap density through the use of a forming gas anneal and achieve a near-ideal subthreshold slope of ~ 69 mV/dec, as well as a high intrinsic carrier mobility of ~ 145 cm² V⁻¹ s⁻¹, which is $\sim 4\times$ higher than its SiO₂ counterpart. The improved device performance can be attributed to the FG anneal of the MoS₂/Al₂O₃ interface and the resultant high-k dielectric screening effect. This study emphasizes the effects of the backside dielectric layer on top-gate device performance, a significant component which must to be thoroughly understood in order to apply TMDs to current CMOS technology.

See [supplementary material](#) for the methods used for the extraction of interface trap density (D_{it}), subthreshold slope, and field effect mobility (μ_{FE}) and the Y-Function method

for the extraction of intrinsic carrier mobility (μ_0) and contact resistance (R_C), as well as the top-gate device cross-section and top-view optical image.

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