Abstract—We report considerable improvement in the hysteresis and reliability of single-layer MoS2 field-effect transistors (FETs) achieved by chemical vapor deposition (CVD) of MoS2 and dielectric encapsulation. Our results show that a high-quality 15-nm thick Al2O3 layer allows for an efficient protection of the devices from adsorbent-type trapping sites. Combined use of the CVD-grown MoS2 as a channel and encapsulation simultaneously leads to at least an order of magnitude smaller hysteresis and up to two orders of magnitude lower long-term drifts of the transistor characteristics. Together with high on/off current ratios (∼100) achieved in our devices, this presents a considerable advance in the technology of MoS2 FETs. As such, we conclude that both CVD growth of MoS2 and encapsulation present important technological steps toward reaching commercial quality standards of next-generation two-dimensional (2D) material technologies.

Index Terms—Single-layer MoS2, encapsulation, reliability, charged traps, hysteresis, bias-temperature instabilities.

I. INTRODUCTION

MOLYBDENUM disulfide (MoS2) is now considered a promising “beyond-graphene” material for applications in next-generation two-dimensional (2D) electronics. In contrast to graphene, MoS2 has a sizable direct electronic bandgap of up to ∼2.6 eV in the single-layer limit [1]–[3], which makes this material attractive for digital device applications. Owing to this, considerable progress in fabricating of single-layer (1L) MoS2 field-effect transistors (FETs) has been demonstrated recently. In particular, numerous single-layer devices with SiO2 [4], [5], Al2O3 [6], HfO2 [4] and hexagonal boron nitride (hBN) [7], [8] gate insulators have been reported. The typical on/off current ratios of these devices are within 104–107, while the subthreshold swing (SS) can reach nearly ideal values down to 74 mV/dec, as already reported for high-k/MoS2/SiO2 devices [4]. In addition, a number of successful attempts at fabricating multi-layer MoS2 FETs have been undertaken [9]–[17], with the best sub-threshold swing of 69 mV/dec achieved for MoS2/high-k devices [17]. However, independent of the number of channel layers, available MoS2 device prototypes often suffer from a sizable hysteresis [5], [8], [10], [14], [15] and long-term drifts of the gate transfer characteristics [8], [11], [13], which are known from Si technologies as bias-temperature instabilities (BTI) [18]–[20]. These issues are typically attributed to charge trapping by both oxide traps [8], [13], [15] and adsorbent-type trapping sites (e.g. water molecules) on the MoS2 channel [5], [8], [10], [11]. While the hysteresis and BTI impede stable device operation at a defined operating point, the reliability of MoS2 prototypes with respect to these issues is still far below the standards of modern commercial FETs [8], [11], [13]. As such, BTI and hysteresis in MoS2 FETs must be addressed prior to commercialization of these next-generation technologies.

Here we report on the improvement of both the reliability and the performance of 1L MoS2 FETs with SiO2 insulator by optimized device processing and encapsulation with a high-quality 15 nm thick Al2O3 layer. Our results show that these devices not only exhibit high on/off current ratio (∼100), but also that both the hysteresis and the threshold voltage shifts due to positive and negative BTI (PBTI and NBTI, respectively) become 1–2 orders of magnitude smaller. Combined with the use of CVD-grown MoS2, this presents a considerable breakthrough in the technology of 2D single-layer materials and devices.

II. DEVICES

Our devices are single-layer back-gated MoS2 FETs with a 25 nm thick SiO2 insulator, 50 nm thick gold source/drain contacts and a 15 nm thick high-quality Al2O3 encapsulation (Fig. 1a,b). Single-layer MoS2 was grown at T = 850 ◦C in Ar atmosphere (760 Torr) by chemical vapor deposition (CVD) directly on SiO2/p++—Si substrates [21]; growth time was 15 minutes. Then, after verification of the superior quality of our CVD-grown MoS2 film [22], the MoS2 FETs were fabricated via a three-step optical lithography process to
of the investigated devices (the contact pads are 100 × (ALD) of Al2O3 were performed at 300 °C after deposition method of [24]. Namely, 120 cycles of atomic layer deposition that might be present on the surface of the MoS2 channel high ALD growth temperature allows to remove impurities of a 1.5 nm thick Al nucleation layer. Note that a relatively our previous work for MoS 2 FETs [8] is that, similarly to exposed MoS2 was etched away with O2 plasma, followed by a second liftoff, the channel widths were defined and the contact extension regions were defined and filled with 50 nm of pure Au, in order to minimize contact resistance [23]. After a second liftoff, the channel widths were defined and the exposed MoS2 was etched away with O2 plasma, followed by a solvent clean to remove the photoresist. Finally, a high-quality Al2O3 encapsulation layer was deposited using a modified method of [24]. Namely, 120 cycles of atomic layer deposition (ALD) of Al2O3 were performed at 300 °C after deposition of a 1.5 nm thick Al nucleation layer. Note that a relatively high ALD growth temperature allows to remove impurities that might be present on the surface of the MoS2 channel before deposition of the encapsulation layer. This Stanford-built ALD setup allows to deposit a high-quality Al2O3 layer with few inherent charge traps.

III. EXPERIMENTAL DETAILS

Electrical measurements were performed in a vacuum (∼ 5 × 10^{-6} Torr) in complete darkness. This was necessary to obtain consistent results for comparison with bare devices which are known to be sensitive to the detrimental impact of environment [5], [10]. First, we measured the drain current vs. gate voltage (I_D − V_G) characteristics using the autorange mode, which was necessary to evaluate the best case on/off current ratio in our devices. Then we analyzed the hysteresis dynamics by measuring the I_D − V_G characteristics using forward (V^+) and reversed (V^-) sweep directions and different measurement frequencies f = 1/(Nt_{sweep}), with N being the number of V_G steps and t_{sweep} the sampling time [8]. Finally, we examined the BTI degradation and recovery dynamics using our experimental technique by applying subsequent stress/recovery cycles with logarithmically increased stress times t_s [8], [25]. A considerable difference compared to our previous work for MoS2 FETs [8] is that, similarly to the technique used for Si devices [26], here a constant gate voltage is applied not only during stress (V_{GS}), but also during recovery (V_{GR}). This leads to more reproducible results, as otherwise the potential at the back gate, which is formed by the Si substrate, shows large uncontrollable drifts.

IV. RESULTS AND DISCUSSION

In Fig. 1c we show the I_D − V_G characteristics measured for our encapsulated CVD-grown MoS2 device at T = 27 °C. The on/off current ratio is at least 10^7, which is larger than previously reported for CVD-grown MoS2. Also, similarly to our previous work on bare exfoliated MoS2 FETs [8], at T = 165 °C (Fig. 1d) the threshold voltage V_{th} of the same device becomes more negative. However, here this issue is less pronounced and thus the measured on/off current ratio remains as high as 10^7, which further underlines the high stability of these encapsulated CVD-grown devices.

In Fig. 2a, b we compare the I_D − V_G characteristics measured for our encapsulated CVD-grown MoS2/SiO2(25 nm) devices, bare devices fabricated using the same method, and bare exfoliated single-layer MoS2/SiO2(90 nm) FETs which are similar to those studied in our previous work [8]. Owing to improved processing technology, CVD-grown devices exhibit considerably steeper subthreshold slopes and larger on current values. Furthermore, the hysteresis, which is sizable for bare exfoliated devices, becomes considerably smaller for bare CVD-grown devices and can be almost completely suppressed for their encapsulated counterparts. In Fig. 2c we compare the hysteresis widths ΔV_{th} normalized by the oxide field factor (V_{MAX} − V_{GMIN})/d_{ox}, with d_{ox} being the oxide thickness, versus the measurement frequency f for three devices. Clearly, the encapsulated CVD-grown device exhibits nearly one order of magnitude improvement compared to a bare device of the same technology and two orders of magnitude compared to the exfoliated bare device. As such, we can conclude that our high-quality Al2O3 encapsulation layer efficiently protects the devices from fast adsorbent-type trapping sites which are in part responsible for the hysteresis in MoS2 FETs.
In Fig. 3a,b we show evolution of the $I_D - V_G$ characteristics and corresponding $V_{th}$ recovery traces measured at the recovery gate voltage $V_{GR} = -0.5\, \text{V}$ after subsequent NBTI and PBTI stresses. Remarkably, the degradation is considerably smaller than has been ever reported for MoS$_2$ FETs. In particular, in Fig. 3c we compare the NBTI and PBTI recovery traces measured after stresses with $t_s = 10\, \text{ks}$ for our encapsulated CVD-grown MoS$_2$ FETs and their bare exfoliated counterparts from our previous work [8]. Since the oxide thicknesses and stress voltages are different, we normalize the threshold voltage shifts by the oxide field $F_{ox} = V_{GS}/d_{ox}$, which is 2.2 MV/cm for exfoliated device and either 4 MV/cm (NBTI) or 4.8 MV/cm (PBTI) for CVD-grown MoS$_2$ FET. While for encapsulated CVD-grown devices both NBTI and PBTI shifts are more than an order of magnitude smaller, they tend to completely recover after several hours. In contrast, the degree of recovery of considerable BTI shifts in bare exfoliated MoS$_2$ FETs for the same time interval does not exceed 40%. Therefore, we conclude that Al$_2$O$_3$ encapsulation, together with our optimized device processing, allows to minimize the amount of slower process-induced defects and adsorbents, which may contribute to charge trapping leading to BTI. As such, we suggest that the observed BTI degradation in our encapsulated devices is dominated by oxide traps in SiO$_2$, which are situated within several nanometers from the MoS$_2$/SiO$_2$ interface and thus can exchange charges with the channel by means of tunneling. As known from Si technologies [27] and our previous works on black phosphorus (BP) [28] and MoS$_2$ FETs [29], these defects are energetically aligned within certain defect bands, with the one contributing to charge trapping in MoS$_2$ FETs located $\sim 2.7\, \text{eV}$ below the SiO$_2$ conduction band edge [27], [28]. This position of the defect band relative to the MoS$_2$ conduction band, together with the Fermi level pinning in accumulation [30], [31], makes NBTI more favorable than PBTI. That is why PBTI degradation in our devices is weaker than NBTI, which is important for MoS$_2$ n-FETs working at positive $V_G$.

Finally, in Fig. 4 we compare initially measured normalized PBTI and NBTI shifts versus $t_s$ for our encapsulated CVD-grown MoS$_2$/SiO$_2$ FETs with those obtained for bare exfoliated MoS$_2$/SiO$_2$ [8], stacked MoS$_2$/hBN [8] and BP/SiO$_2$ [28] devices. Remarkably, the PBTI shifts for our encapsulated MoS$_2$ FETs are around an order of magnitude smaller than in previously studied 2D devices. As for NBTI, encapsulated MoS$_2$ devices studied here can slightly outperform Al$_2$O$_3$ encapsulated BP/SiO$_2$ FETs, which have been previously considered the most stable with respect to room temperature BTI among other 2D devices. Although commercial standards require further improvement of the reliability by at least one order of magnitude, our encapsulated MoS$_2$ FETs present a considerable step forward in this direction.

V. CONCLUSIONS

In summary, we have suggested a versatile way to improve both the reliability and performance of MoS$_2$ FETs by optimization of the device processing conditions and the use of a high-quality Al$_2$O$_3$ encapsulation to protect the devices from adsorbent-type trapping sites. While already having an extremely high on/off current ratio of $\sim 10^9$, our devices also exhibit a considerable improvement in terms of hysteresis and BTI stability. As such, we conclude that high-quality encapsulation of MoS$_2$ FETs, together with CVD growth of MoS$_2$ film, present an important technological step toward reaching commercial quality standards of these new technologies.