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Correlating Electronic Transport and 1/*f* Noise in $MoSe_2$ Field-Effect Transistors

Jiseok Kwon[1,2], Abhijith Prakash[1,2], Suprem R. Das[3,4,*], David B. Janes[1,2,*]

[1] School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907

[2] Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907

[3] Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan KS 66506

[4] Department of Electrical and Computer Engineering, Kansas State University, Manhattan, Kansas 66506

* Contact authors: janes@purdue.edu, srdas@ksu.edu

Two-Dimensional Transition Metal Dichalcogenides (2D-TMDCs) such as MoS_2, $MoSe_2$, WS_2, and WSe_2 with van der Waal's type interlayer coupling is being widely explored as channel materials in a Schottky Barrier Field Effect Transistor (SB-FET) configuration. While their excellent electrostatic control and high ON/OFF ratios have been identified, a clear correlation between electronic transport and the low-frequency noise with different atomic layer thickness is missing. For multi-layer channels in MoS_2 FETs, the effects of interlayer coupling resistance on device conductance and mobility have been studied, but no systematic study included interlayer effects in consideration of the intrinsic (channel) and extrinsic (total device) noise behavior. Here we report the 1/*f* noise properties in $MoSe_2$ FETs with varying channel thickness (3 to 40 atomic layers). Contributions of channel vs. access/contact regions were extracted from current-voltage (transport) and 1/*f* noise measurements. The measured noise amplitude shows a direct crossover from channel- to contact-dominated noise as the gate voltage is increased. The results can be interpreted in terms of a Hooge relationship associated with the channel noise, a transition region, and a saturated high-gate voltage regime whose characteristics are determined by a voltage-independent conductance and noise source associated with the metallurgical contact and the interlayer resistance. Both the channel Hooge coefficient and the channel/access noise amplitude decrease with increasing channel thickness over the range of 3 to 15 atomic layers, with the former remaining approximately

constant and the latter increasing over the range of 20 to 40 atomic layers. The analysis can be extended to devices based on other TMDCs.

KEYWORDS: $MoSe_2$ transistors, Transition metal dichalcogenides, 1/*f* Noise, Schottky barrier, van der Waal solid beyond graphene, Interlayer coupling.

I. INTRODUCTION

Two-dimensional atomic crystals, especially transition metal dichalcogenides (TMDCs) such as MX_2 (M ≡ Mo, W and X ≡ S, Se) have shown fascinating electronic and optical properties, are of interest for future nanoelectronic, optoelectronic, and nanophotonic devices. [1–4] Multi-layer TMDC materials show layer stacking via van der Waal interaction between layers. Characteristics such as an indirect to direct bandgap crossover [5,6], formation of strongly correlated many-body bound states in monolayers [7–9] and tunability in band gap between 1.0 eV and 2.0 eV make 2D-TMDCs attractive for fundamental as well as applied research. [10–14] A number of TMDCs have been used as channel materials in FETs, yielding devices with low off-current, ON/OFF ratio above 10^6, high field effect mobility, and near 60 mV/decade subthreshold swings. [15–19] There are also recent demonstrations of fully integrated circuits and logic building blocks (such as an inverter, NAND gate, static RAM and five-stage ring oscillator) from 2D FET devices. [20–25]

Contacts play a very important role in the charge injection process into the channel of a back-gated SB-FET, particularly for the metal source/drain contacts typically employed to TMDCs. [10,26] In a study on MoS_2 FETs comparing contact metals with various work functions, Das *et al.* [17] showed a significant change in extrinsic mobility over the range of work functions, with the highest performance observed for the lowest work function material (scandium). There have been detailed transport measurements focused on microscopic analysis of channel materials as well as channel-metal contact effects (both room and low temperature). [27,28] Low-frequency (1/*f*) noise, a ubiquitous phenomenon in every electronic device, has not been well understood and correlated to transport features in these 2D FET devices.

Low-frequency (1/*f*) noise, a fundamental technique in characterizing semiconducting materials and devices [29–31], has also become valuable in characterizing nanoscale materials and devices, shedding light on the microscopic origin of transport fluctuations, and providing a means to evaluate electronic states at the channel/dielectric interface. Low-frequency device noise can also have significant implications on circuits and systems (such as circuits for RF communications). The noise properties are dependent on the interaction of carriers with the channel/dielectric interface states as well as the contact and access-region properties. Therefore, it is essential to characterize the 1/*f* noise of devices consisting of low dimensional materials such as nanowires, carbon nanotubes, graphene, and TMDCs. [32–38] Furthermore, 2D van der Waal channel materials (graphene, TMDCs) are expected to show unique noise characteristics due to the existence of interlayer resistances between the individual ultra-thin channel layers and the presence of grain-boundaries as transport barriers in case of large scale 2D channels (typically grown using chemical vapor deposition techniques). Indeed, in recent studies some of these features have been demonstrated in noise characteristics: for example, the contrasting nature of 1/*f* noise in single layer graphene (SLG) and bilayer graphene (BLG) has been studied by Min *et al.* and interpreted in terms of their unique band structure. [39] There are several reports of noise in transistors with TMDC channels. The impact of strong localization with a five order of magnitude higher 1/*f* noise along the grain boundaries of CVD MoS_2 compared to the inter-grain noise has been shown recently by Hsieh *et al.* [40] In prior studies on noise in various TMDC transistors, the gate-voltage and/or current dependences have been interpreted in terms of various noise mechanisms, including McWhorter (number fluctuation) model, Hooge (mobility fluctuation) model, or a transition from Hooge to McWhorter models. [37,41–43] Some prior studies in TMDC FETs with relatively thin channel layers have shown behavior consistent with a McWhorter model, either within a channel-dominated regime above threshold [44] or over a bias range spanning sub-threshold and above threshold (e.g. weak versus strong "inversion"), but without explicitly considering contact effects. [43] However, other studies have observed behavior that is consistent with a Hooge mechanism over a significant gate voltage range (above threshold voltage). [37,45] Combined number fluctuation/correlated mobility fluctuation models have also been discussed. [41,42] Na et al. [41]studied unpassivated and passivated MoS2 devices (~18 layers) and analyzed the results with a mixture of Hooge and McWhorter models but observed Hooge behavior in "bulk" (~62 Layer) devices. Other studies also showed the interpretation with the unified model of carrier number fluctuation and correlated mobility fluctuations in single-layer chemical-vapor deposited [46] and thick-layer (75 Layers) TMDC FETs. [47] A transition from Hooge regime to McWhorter regime with increasing I_d in these studies generally ignores the contact effects, which could be responsible to the observed transition in noise behavior. In general, these studies indicate that noise behavior is different in strong versus weak "inversion" regimes and that increased layer thicknesses yield lower noise than single/few layer devices. However, it is difficult to draw specific conclusions regarding what device parameter or material choice yields a specific dominant noise mechanism. For example, Hooge behavior is observed for thin layers (monolayer and bilayer) in some cases but for bulk layers in other studies. [48] Some studies have considered contact and channel effects [44,49], but consideration of noise properties versus layer thickness has been limited and a comprehensive model for layer-thickness dependence is not available. A more thorough understanding of 1/*f* noise behavior, including consideration of channel thickness and contributions of contacts, should enable better device structures, which will be important for sensors, [50] digital and analog electronics, [51] as well as linear circuits for radio frequency communications. [52]

The current study focuses on multilayer $MoSe_2$ FET devices with channels of various atomically controlled thicknesses. Analogous to MoS_2, $MoSe_2$ shows tunable energy gap and crossover from indirect to direct bandgap in the monolayer limit. [53–55] However, in our observation, $MoSe_2$ FETs have shown higher ambient stability for prolonged duration with minimal hysteresis during forward and reverse bias conditions. Several other unique characteristics of $MoSe_2$ over MoS_2 are (1) degenerate indirect and direct bandgap with decoupling of bulk and 2D limit, [55] (2) angle resolved photoemission spectroscopy (ARPES) shows the dispersion of the valence bands decreases along $k_{\square\square}$ and $k_{\perp}$ directions, indicating increased 2D character (or increased interlayer distance). [56] (3) $MoSe_2$ shows much weaker bound exciton peak compared to MoS_2, therefore, having a faster photoresponse time (~ three orders of magnitude faster; 25 ms compared to < 30 s for MoS_2) than MoS_2, indicating potential application in efficient phototransistors. [57] (4) the atomic defects (Mo-Se defects) in $MoSe_2$ are reported to be less significant than the Mo-S defects in MoS_2. [58] These properties, along with observed transistor characteristics, make $MoSe_2$, a promising material for nanoelectronic and optoelectronic device applications. While the transport properties of $MoSe_2$ FETs have been reported, $1/f$ noise characterization has not been considered in detail, e.g. to include consideration of the channel and contact noise in terms of the channel thickness. [49,59]

Herein, we present an experimental study of the current-voltage relationships and gate-bias dependent $1/f$ noise in $MoSe_2$ transistors with channel thicknesses varying from 3 to 40 atomic layers. For a given layer thickness, the gate-bias dependences of both the conductance and noise at low drain fields (linear regime) can be understood in terms of noise contributions and conductance from the channel and contact/access regions. The model developed in the current work can fit voltage dependence without the need to assume a voltage-variable noise mechanism within the channel. Our study shows that the voltage dependence can be fit by a model considering a transition from channel-dominated noise to contact-dominated noise, and that a single noise mechanism is satisfactory to explain the channel contribution to noise. Comparison of properties of devices with varying layer thicknesses allows both qualitative and quantitative comparison of the intrinsic channel properties (mobility and Hooge parameter) and the contributions from the contact and interlayer coupling resistances. As the layer thickness increases over the range of 3-15 monolayers the mobility increases, and noise amplitude decreases, consistent with decreasing interactions between carriers and interface states. For thickness of 20 layers and beyond, increasing layer thickness leads to decreased extrinsic mobility and increased noise amplitude, associated with increased series resistance involved with interlayer coupling resistance.

II. EXPERIMENTAL DETAILS

$MoSe_2$ layers of various atomic thicknesses were exfoliated on Si/SiO_2 (90 nm) substrates using mechanical exfoliation method and their locations were identified using predefined alignment markers on the Si/SiO_2 substrates. Precisely, $MoSe_2$ layers with 3L, 5L, 8L, 10L, 15L, 20L, and 40L were selected for FET device fabrication. L stands for a single molecular layer of $MoSe_2$ solid. High quality bulk $MoSe_2$ crystals (from *2D Semiconductor, Inc.*) were used to obtain the above flakes with mechanical exfoliation. The thicknesses of the flakes were determined by atomic force microscopy and the quality of the flakes was evaluated using Raman spectroscopy (with laser excitation wavelength of 532nm). 50 nm thick nickel was used as source/ drain (S/D) contact electrodes in the transistor structure. The channel length of each of the devices was kept 2µm and the channel widths, determined by the flake dimension, were kept approximately between 2µm and 4µm. A semiconductor parameter analyzer, electrical probe station, and arrangements for 1/*f* noise measurements were used for the transport and noise characteristics study of all the above FETs. More details of the device fabrication and measurement set up were provided in Appendix A.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the schematic view of the nickel S/D and back-gated $MoSe_2$ FET structure studied in this study. Figure 1(b) shows the AFM image and step profile of a representative $MoSe_2$ flake that forms the channel of a FET with thickness around 9.7nm, corresponding to ~15 molecular layers (single layer thickness of $MoSe_2$ ~ 0.65nm). [60] Figure 1(c) shows the Raman spectrum of a representative flake (15 layers), acquired near its center (the laser spot size is ~1µm in diameter and hence could be well focused at the center of the flake whose area is few square micrometers). The two primary Raman peaks, measured at positions of 243.42cm^{-1} and 286.32cm^{-1}, are assigned to the A_{1g} and E^1_{2g} vibrational modes, corresponding to the out-of-plane and in-plane lattice vibration, respectively.

The electrical characteristics were measured in ambient conditions with electromagnetic and light shielding (see Appendix A for more details). Note that the devices studied in the present work are back-gated SB-FETs having a fraction of the channel itself buried underneath the S/D contacts, consequently the contribution of these portions in the carrier transport is critical for the device analysis [10]. Models which include the impact of these channel segments on carrier transport in both the OFF state [10]and the ON state [26] are reported previously for WSe_2 FETs and MoS_2 FETs respectively. In the present work on $MoSe_2$ FETs we follow the ON state model for the transport data analysis and discussion [26].

Figure 2(a) shows the measured low field (drain-source voltage (V_{ds}) of 0.2V) transfer characteristics of FETs with the indicated layer thicknesses. At a given gate-source voltage (V_{gs}), the drain current (I_d) increases with increasing layer thickness over the range of 3L to 15L. The 20L and 40L devices show a saturation with increasing V_{gs}, consistent with series resistance effects. A similar trend in drain current maxima has been reported in MoS_2 FETs with low Schottky barrier height electrodes, with a ~ 9L thick channel producing the optimum current.[27] The threshold voltage (V_{th}) of each of the devices were obtained by extrapolating the low-field I_d-V_{gs} relationship to I_d=0.

The transconductance ($g_m = dI_{ds}/dV_{gs}$) is dependent on V_{gs}; the maximum value is used to calculate the extrinsic mobility ($\mu_{ext.}$) at low drain field (V_{ds} = 0.2V), using

$$\mu_{ext} = \frac{dI_{ds}}{dV_{gs}} * \frac{L}{W} * \frac{1}{C_{ox}} * \frac{1}{V_{ds}} \qquad [1]$$

where L and W are the channel length and width, respectively, and C_{ox} is the gate oxide capacitance per unit area (3.84 x 10^{-4} F/m^2 for 90 nm SiO_2). (The extraction of $\mu_{ext.}$ is described in Appendix C). Figure 2(b) shows the measured $\mu_{ext.}$ and the intrinsic mobility (μ_{int}, discussed later) as functions of $MoSe_2$ layer thickness. The rise of extrinsic field effect mobility with channel thickness (number of layers), observation of maximum value (at 15L) and decrease beyond 15L indicates the dominant role of the access resistances arising from S/D contacts and the interlayer coupling beyond 15L. Comparable behavior has been observed by *Das et al.* in MoS_2 transistors and analytically modeled using a resistance network model. [26]

The measured I-V relationships and $\mu_{ext.}$ reflect extrinsic values, i.e. they contain contributions from series resistance (R_1) as well as from the channel. The total extrinsic resistance, R_{total}, is the sum of R_1, which is expected to be independent of V_{gs} in the ON state, and the channel resistance (R_{ch}), i.e.

$R_{total} = R_1 + R_{ch}$ [2]

R_1 is calculated from the intercept of the relationship between R_{total} and the inverse of V_{gs}-V_{th} (shown in Appendix B). [61] The extracted values of R_1, and R_1 normalized by W, are shown for devices with various thicknesses in Table 1. Given the nature of the 2D van der Waal's solids, in general, R_1 will contain contributions from the metal-semiconductor contact resistance (R_S) as well as the interlayer coupling resistance (R_{int}) between n number of layers. In a limit in which n is significantly larger than the number of layers contributing to channel conductance, one would expect a relationship comparable to:

$R_1 = R_s + nR_{int}$ [3]

In order to quantify the channel behavior, one needs to obtain intrinsic values, i.e. without the effects of contacts/access resistances. To calculate μ_{int} the actual drain voltage across the channel (V_{ds}') is calculated using

$V'_{ds} = V_{ds}(R_{total} - R_1)/R_{total}$ [4]

and

$\mu_{int} = \frac{dI_{ds}}{dV_{gs}} * \frac{L}{W} * \frac{1}{C_{ox}} * \frac{1}{V'_{ds}}$ [5]

where n is the number of $MoSe_2$ layers and R_{int} is the interlayer resistance. As shown in figure 2(b), following this correction, $\mu_{int.}$ remains relatively constant for layer thicknesses above 15L (~ 55 $cm^2/V{\bullet}s$).

For layer thicknesses below 15L, μ_{int} increases with increasing layer thickness. As discussed in prior studies, in few-layer devices, carrier scattering in the channel impacts the current injection as well as the mobility. [26] A number of atomic layers are required to screen such scattering effects and achieve the optimal mobility. Beyond this thickness, $\mu_{int.}$ should remain relatively constant, as observed. However, R_1 increases with increasing layer thickness due to effects of interlayer coupling, which leads to a decreasing μ_{ext}.

The 1/*f* noise characteristics, an ubiquitous yet a key limiting factor that needs to be addressed in low-dimensional electronic devices, are of interest in terms of both the properties of the channel, e.g. channel-oxide interface, and the contributions from series resistance. Absence of such a study systematically in 2D TMDC devices, particularly the one relating to the transport and noise in the same devices and with number of atomic layer channel thicknesses, would provide a direct correlation among these parameters insisting better and accurate design considerations of such devices for optimal performance.

Figure 3(a) shows the normalized noise current spectral density (S_I/I_d^2) vs. frequency (f) between 1 Hz and 1 kHz for $MoSe_2$ FETs with various channel thicknesses. The measurements were performed at V_{ds} = 50 mV, to maintain operation in the linear regime) and an over-drive voltage (V_{gs}-V_{th}) of 7V for all the devices. All the FETs follow a nominal 1/*f* relationship (dotted line). Figure 3(b) show the total noise amplitude ($f*S_I/I_d^2$), along with the channel and contact/access contributions (discussed later), at f=100 Hz vs. the number of layers. The total noise clearly demonstrates a significant decrease of 1/*f* noise with increasing channel thickness up to 15L. Beyond 15L, the total device noise increases gradually. The behavior for small number of layers is consistent with significant scattering from impurities and/or interface states (localized electronic states and Coulomb potentials from the substrate have been proposed earlier [62]). As the layer number increases to 15, the channel screens such effects (observation of a charge transport localization within several layers in TMDC channel has been shown previously [63]) Moreover, the increase in the total device noise beyond 15 layers most likely is associated with access resistances involving the contact resistances, excess channel resistances, and interlayer coupling.

Figures 4(a) and 4(c) show the measured noise amplitude vs. (V_{gs}-V_{th}) for representative $MoSe_2$ FETs (15L and 40L respectively, black solid circles). In order to allow comparison to the experimental data, the corresponding model (discussed later) is also shown, with blue and red dotted lines representing terms associated with the channel and contact noise sources, respectively, and the green line representing the overall model. In order to compare our experimental data and model to that expected from a McWhorter model, we have included $(g_m/Id)^2$ vs V_{gs}-V_{th} curves in the same plots for 15L and 40L FETs. Corresponding figures for devices with all other channel thicknesses discussed in this work are shown in SI. Over the voltage range considered, the $(g_m/Id)^2$ relationship exhibits a different gate voltage dependence than the experimental noise amplitude. For layer thicknesses above 8L, this effect is prominent even if one restricts the voltage range to the channel-dominated regime. Similar conclusions can be reached if one considers the $(V_{gs}$-$V_{th})^{-2}$ dependence associated with a McWhorter mechanism [43,44]; such behavior is not observed in the experimental data. The model considered in this study, which utilizes a Hooge noise model plus contact effects, fits the data much better than a McWhorter model.

For overdrive voltages below ~ 10V (~9V) for 15L (40L), the data follows approximately an inverse relation with overdrive voltage, as expected for noise dominated by mobility fluctuation (Hooge model). [32,64] At large overdrive voltages, the noise amplitude saturates, as expected in regimes in which the series resistance dominates both noise and resistance. [32,44,64] Qualitatively similar behavior is observed for the FETs with other thicknesses in this study (Supporting Information V, Figure S4, showing results for 3L, 5L, 8L, 10L, and 20L). The dependencies on both voltage and layer thickness can be explained using a model considering the effects of both the channel and the series resistance, as shown by the green curve in Figure 4(a) and Figure 4(c) and explained in the following section.

As with the conductance/mobility behavior, the noise behavior can be separated into contributions from the channel and from the series resistance. Following previous approaches for separating channel and contact noise contributions in transistors, [32,44,65] it is convenient to transform into resistance spectral power density for the overall device (S_{Rtotal}) and to consider contributions of noise sources and resistances associated with the channel and series resistance:

$$\frac{S_I}{I_d^2} = \frac{S_{Rtotal}}{R_{total}^2} = \frac{S_{R1}+S_{Rch}}{(R_1+R_{ch})^2} \quad [6a]$$

which can be rearranged to:

$$\frac{S_I}{I_d^2} = \frac{S_{R1}}{R_1^2} \cdot \frac{R_1^2}{(R_1+R_{ch})^2} + \frac{S_{Rch}}{R_{ch}^2} \cdot \frac{R_{ch}^2}{(R_1+R_{ch})^2} \qquad [6b]$$

Here, $\frac{S_{Rch}}{R_{ch}^2}$ and $\frac{S_{R1}}{R_1^2}$ are the normalized noise resistance power spectral densities for the channel and series (contact and interlayer) resistance, respectively. For each device, the parameters on the right side of Eq. 6b are extracted at a common V_{ds} (0.2V) as follows. For resistances, R_{total} is determined at each V_{gs} (above threshold) from the corresponding measured I_{ds}. R_1 is determined as stated earlier and assumed to be independent of V_{gs}. At each V_{gs}, $R_{ch}(V_{gs})$ is determined from $R_{total}(V_{gs})$ and R_1, using Eq. [2]. Figure 4(b) shows the extracted $R_{ch}(Vgs)$ and R_1 for the representative 15L device, along with the corresponding noise power densities (discussed layer). A cross-over from channel-dominated ($R_{ch} > R_1$) to series-resistance dominated ($R_{ch} < R_1$) behavior is observed at approximately V_{gs}-V_{th} = 19V (additional devices shown in Appendix D). Such a transition for 40L $MoSe_2$ FET is shown in Figure 4(d) with the resistance cross-over point at a much lower voltage (approximately 9V).

The total noise amplitude, e.g. the data in Figure 4(a) and Figure 4(c) for 15L and 40L respectively, is used along with the resistances R_{total}, R_1 and R_{ch}, to calculate the noise sources S_{R1} and S_{Rch}. First, the Hooge parameter is extracted using the small overdrive voltage regime, in which the measured S_I/I_d^2 exhibits a voltage dependence of ~ $(V_{gs}$-$V_{th})^{-1}$ and therefore $S_{Rch} >> S_{R1}$ is a reasonable assumption. Next, the value of S_{Rch} at the maximum measured overdrive voltage is calculated using the Hooge relationship. The value of S_{R1} is obtained by evaluating Eq. 6b at this voltage, i.e. using the bias-independent R_1 and the R_{ch}, S_{Rch} and measured S_I/I_d^2 values corresponding to this voltage. Finally, S_{Rch} is determined at other gate voltages using Eq. 6b, with the corresponding R_{ch} and measured S_I/I_d^2 values. The extracted S_{R1} and S_{Rch}

values for the representative 15L device and 40L device are shown in Figure 4(b) and Figure 4(d) respectively, and for devices with other thicknesses in Appendix D. Several regimes are observed. For modest (V_{gs}-V_{th}) values, the total noise is dominated by the S_{Rch} term and follows a Hooge relationship, as evidenced by a gate voltage dependence close to $(V_{gs}\text{-}V_{th})^{-1}$. A noise crossover point ($S_{Rch} = S_{R1}$) is observed, occurring at approximately $V_{gs} - V_{th} = 21.5$V for the 15L device. The region between the resistance cross-over point and the noise cross-over point, as indicated by shaded region in Figure 4(b), represents a transition region in which ($R_{ch} < R_1$) but ($S_{Rch} > S_{R1}$). Within this region, the noise amplitude is expected to follow a voltage relationship different than either the low V_{gs} (channel dominated) regime or the high V_{gs} (series resistance dominated) limit. [31,64] For the 40L device, qualitatively similar behavior is observed (Figure 4(d)), but with a noise crossover voltage at approximately $V_{gs} - V_{th} = 10$V and a much narrower transition region. The effect of the narrower transition region is evident in Figure 4(c) where there is distinct variation from channel-dominated to contact-dominated noise regimes without a clear intermediate V_{gs} dependence. The availability of noise and resistance parameters allows calculation of the overall voltage dependence of the noise amplitude using Eq. 6b. Figure 4(b) and 4(d) show the contact/access (first term in Eq. 6b) and channel (second term) contributions to the noise amplitude, along with the overall amplitude (sum of the two terms) for 15L and 40L devices, respectively. Comparable plots for devices with other layer thicknesses are shown in Supporting Information. The overall amplitude, i.e. full right side of Eq. 6b (green line), matches well with the measured value over the entire voltage range. For overdrive voltages below ~ 15V, the behavior is dominated by the channel contribution and follows a $V_{gs}^{-1.1}$, consistent with a mobility fluctuation (Hooge) noise model. The channel contribution rolls off for V_{gs} values above ~ 15V due to the resistance factor in second term of Eq. 6b; R_{ch} is monotonically decreasing while R_1 remains constant. The collective effect of the resistance and S_R transitions is a transition region in the noise amplitude, with~ $V_{gs}^{-2.75}$ dependence for this representative device. For voltages beyond this transition region, V_{gs}^{0} behavior is observed, as expected for a regime in which the series resistance dominates both noise and resistance. Similar channel and noise data extraction analysis was performed for all the devices, and the corresponding values are listed in Table 1.

The extracted channel, series resistance and total noise amplitudes are plotted along with the corresponding measured data in Figure 6(a). All the devices show a clear transition from a region following the Hooge relationship to a V_{gs}^0 regime. However, the relationships are quantitatively different with respect to changes in transition voltages, voltage range and limiting values. In order to allow comparison of the channel and contact/access contributions to noise at a common bias point, the normalized noise amplitudes, transformed back to S_I/I_d^2 using Eq. 6b, are plotted for an overdrive voltage of 7V in Figure 3(b). This overdrive voltage allows comparisons of all devices in the regime in which the channel noise term dominates, although the 40L device is at a bias point at which the R_I term starts to contribute. As observed in Figure 3(b), the contact/access contribution is smaller than the channel term for all devices, as expected based on the choice of overdrive voltage. Qualitatively similar behavior would be expected at other bias points within the channel-dominated regime. The observation of a contact/access contribution that decreases significantly with layer thickness (3L to 15L) is consistent with an overall decrease in series resistance over that regime. The increase in this noise contribution at larger layer thicknesses is qualitatively consistent with expected dependence of adding noise sources corresponding to interlayer coupling resistances, both in terms of the observed increase in R_I and the additional noise power spectral density (S_{RI}). However, as evidenced by the dependence of R_I values versus layer thickness, which does not follow the simple model described in Eq. 3, attributing specific contributions to metallurgical contact versus interlayer resistance effects is somewhat difficult.

The observation of a clear channel-dominated regime, which follows the Hooge relationship [29,49],

$$\frac{S_I}{I_d^2} = \frac{\alpha_H}{f \cdot N} \quad [7]$$

, where S_I is the current noise power spectral density, I_d is the drain current in the channel, f is the frequency and $N = \frac{C_{ox}}{q} * \left(V_{gs} - V_{th}\right) * LW$ is the total number of charge carriers in the channel, allows quantitative comparison of channel noise properties through the α_H values. In this regard, a rearrangement of Eq. 7 in the channel-dominated regime gives

$$f * \frac{S_I}{I_d^2} = f * \frac{S_{Rch}}{R_{ch}^2} = \frac{q*\alpha_H}{C_{ox}*LW} * \frac{1}{(V_{gs} - V_{th})}. \quad [8]$$

Using Eq. 8, the Hooge parameter, α_H, (quantifying channel noise property and excluding effects of R_1 and S_{R1}) can be extracted from linear fitting within the channel-dominated regime, i.e. the region of Figure 4(a) and Figure 4(c) showing a slope of ~ V_{gs}^{-1}. This analysis yields an α_H value for each layer thickness. The corresponding values are tabulated in Table 1, along with values of R_1 and S_{R1}, which describe the contact/access resistance parameters. The Hooge's parameter vs. atomic layer number is shown in Figure 6 (b). Hooge's constants were extracted in voltage region in which the channel is dominating both noise and resistance, i.e. in which the term containing S_{Rch} and R_{ch} dominates. The Hooge parameter is considered to be a figure of merit for the channel region and should be independent of contact/access resistances. Broadly, the decrease in Hooge parameter with increasing layer thickness (3L to 15L) can be attributed to decreasing interactions of the channel charge with oxide/interface trap states. Beyond 15L, the centroid of the channel distribution is not expected to change significantly, as evidenced by a relatively constant intrinsic mobility, so the Hooge parameter and the channel/interface trap interaction is expected to remain relatively constant. Figure 6(c) illustrates the equivalent circuit model involving case of a channel noise current source (S_{Ich}) in series with noise current sources representing the metal/semiconductor contact (S_{IS}) and multiple interlayer resistances (S_{Iint}), along with the associated parallel resistances. To add such series sources, it is necessary to convert to Thévenin equivalent resistance noise sources, such as the one illustrated in the Figure 6(d). The overall noise spectral power density is $S_{Rtotal} = S_{R1}+S_{Rch}$, where S_{R1} is expressed as $S_{R1}=S_{Rs}+n\cdot S_{Rint}$. The overall resistance can be obtained by adding the series-connected resistances. Because the contact resistance and interlayer coupling resistance are not negligible, we model that both the contact and the interlayer resistances contribute to the measured noise.

In order to investigate the channel length dependence of the noise, we fabricated 8L $MoSe_2$ FETs with different channel lengths (L_{ch}=0.5μm, 1μm and 2μm) on the same flake. The dimensions and contact electrical parameters are presented in Table 1. Figure 5 presents the measured noise amplitude versus (V_{gs} – V_{th}) for the devices, along with the model (channel noise term, contact noise term and total) corresponding to the 2μm channel length. The measured $(g_m/I_d)^2$ relationship is also shown for the 2μm channel length; as with the devices shown in Figure 4, this relationship did not fit the experimental data as well as the model which considered Hooge model and contact effects. Using comparable analysis to that described previously, values of S_{R1} and Hooge parameter are extracted for the devices and presented in Table 1. The observation of comparable Hooge parameters for devices with varying channel lengths is consistent with the behavior expected in a channel-dominated regime (as labeled in Figure 5). Qualitatively similar results are also observed in 3L FETs with different channel lengths. (See Appendix E for more details). In order to allow direct comparison between devices with various channel lengths, the area scaling of noise in 3L and 8L FETs is presented in Appendix F. It is informative to compare the noise results in this study to both prior thickness-dependent mobility studies and noise studies. Prior studies have attributed the increasing mobility with increasing layer thickness to Thomas-Fermi screening, resulting in decreased scattering by interface states. [26] Since interface states are generally thought to be responsible for the noise, one would also expect a decreasing channel contribution to noise amplitude with increasing layer thickness. Noise amplitude can also be compared, e.g. to that of Paul, et al. [43] Although that study observed voltage-dependent noise that followed a carrier density fluctuation model, the noise amplitudes for few-layer devices for voltages just above threshold (as defined in the current study) are comparable to those observed in the 3L and 5L devices at comparable overdrive voltages in the current study. The devices in the current study employ a ~ 3x thinner SiO_2 gate dielectric, resulting in a ~ 3X larger sheet carrier density at a given overdrive voltage. Paul, et al. inferred metallic-regime behavior for gate voltages corresponding to an overdrive voltage of ~ 3V; for the devices in the current study, the sheet carrier density is at the corresponding level or higher for overdrive voltages above ~ 1V.

Prior studies on FETs with TMDC channels have observed comparable behavior in the transition regions between channel-dominated and contact/access dominated noise regimes. [41,42] In some cases, the transition has been interpreted as a change in the dominant channel noise mechanism from a mobility-fluctuation (Hooge) mechanism to a carrier-density fluctuation (McWhorter) mechanism, which would exhibit a V_{gs}^{-2} dependence. [30,44] However, the voltage-dependence of the noise amplitude can be modeled using the channel and contact/access contributions discussed above, with a single physical model for the channel contribution. The voltage dependence in the transition region can be explained by the sequential transitions of resistance and noise from channel-dominated to contact-dominated regimes. Such a model is found to be valid across the full range of layer thicknesses considered in this study, with the same channel noise mechanism in all devices.

IV. CONCLUSIONS

In conclusion, in the present work we have provided a comprehensive study of the correlation between the electrical transport and $1/f$ noise studies in $MoSe_2$ FETs with varying channel layer thicknesses. The obtained mobility versus layer thickness of $MoSe_2$ FETs can be understood in terms of an intrinsic component associated with the channel and a component attributed to contact/interlayer coupling resistance, which both change with layer thickness. The gate-voltage dependence of the noise amplitude can be understood in terms of a voltage-dependent channel-dominated component and a voltage-independent contact/access dominated regime. A quantitative model is developed which adequately describes the observed voltage dependence, and which allows extraction of channel versus contact/access parameters for each layer thickness. Although previous studies on multi-layer TMDC FETs have attributed voltage dependence of noise amplitude to a transition from Hooge noise mechanism to McWhorter behavior, a model considering both channel and contact/access resistance contributions can fit the observed voltage dependence for devices across the full range of layer thicknesses using only one mechanism (Hooge's mobility fluctuation). The Hooge's constant (2.64×10^{-3}) extracted from the channel-dominated regime for the 15-layer device is comparable to values reported for reliable nanoscale FETs.

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APPENDIX A: Device fabrication

Using mechanical exfoliation technique, high quality crystalline $MoSe_2$ flakes (from *2D Semiconductor, Inc.*) were transferred onto highly doped Si/SiO_2 wafers (SiO_2 thickness of 90nm) with pre-defined alignment markers. $MoSe_2$ flakes were first identified using an optical microscope, and the thickness of each flake was determined using an atomic force microscope (AFM). FETs were fabricated using seven of the $MoSe_2$ flakes, with thicknesses listed in Table 1, as the channel material. Source and drain (S/D) contact electrodes were defined by e-beam lithography (Raith e_LiNE) followed by 50 nm nickel e-beam evaporation and liftoff.

A Keithley 4200 semiconductor parameter analyzer and probe station were used for the transport measurements and an Agilent Technologies 35670A dynamic signal analyzer, low noise current pre-amplifier (Stanford Research SR570), and voltage source were used for the 1/*f* noise measurement. All the grounding terminals from the equipment were connected to an instrument ground system.

APPENDIX B: Extraction of series resistance for the $MoSe_2$ FETs

The series resistance (R_1) is extracted from the measured device resistance versus gate voltage relationship, by plotting the total resistance (R_{total}) vs. 1 / (V_{gs}-V_{th}) and extrapolating the line to the y-axis

(Figure B). The extracted R_1 was employed for the analysis of mobility and noise parameters. For 15L and 40L, the series resistances were 21KΩ and 187KΩ, respectively.

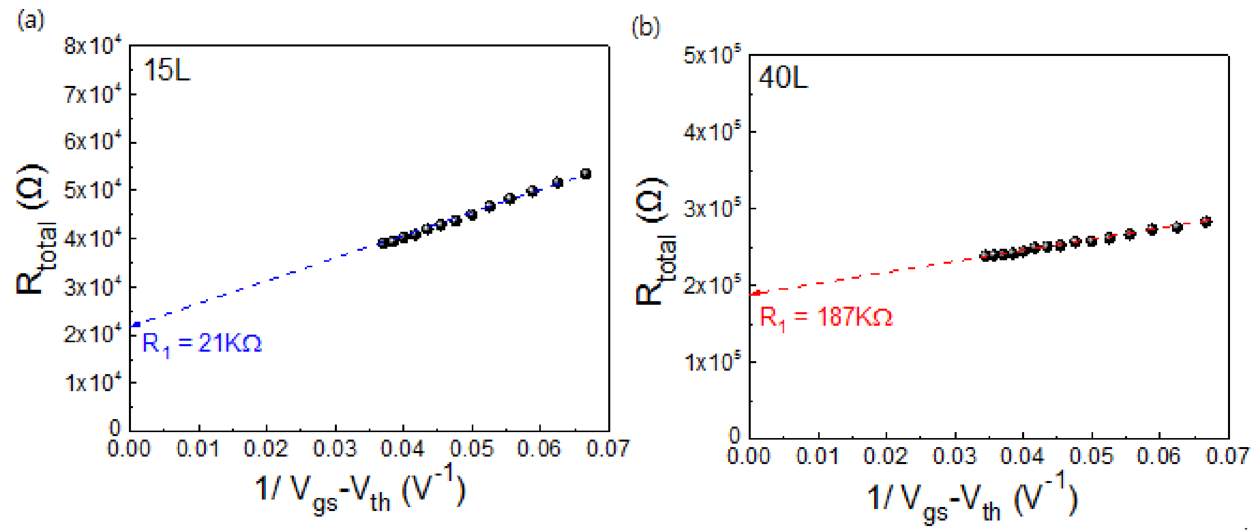


Figure B. Total resistance vs. 1 / (V_{gs}-V_{th}) for the extraction of series resistance, (a) 15L and (b) 40L.

APPENDIX C: Extraction of field effect mobility for $MoSe_2$ FETs

The transconductance is obtained by first order differentiation of the transfer characteristic (Figure C). The peak g_m is then used to calculate the extrinsic field effect mobility was obtained by using the equation $\mu_{ext} = \frac{dI_{ds}}{dV_{gs}} * \frac{L}{W} * \frac{1}{C_{ox}} * \frac{1}{V_{ds}}$.

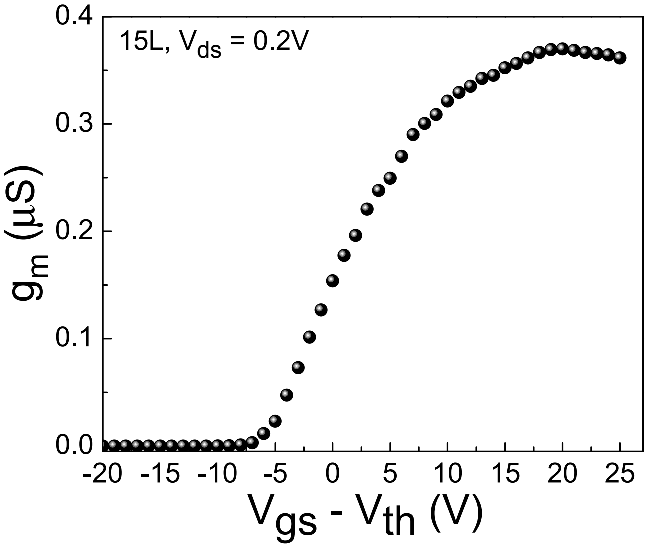
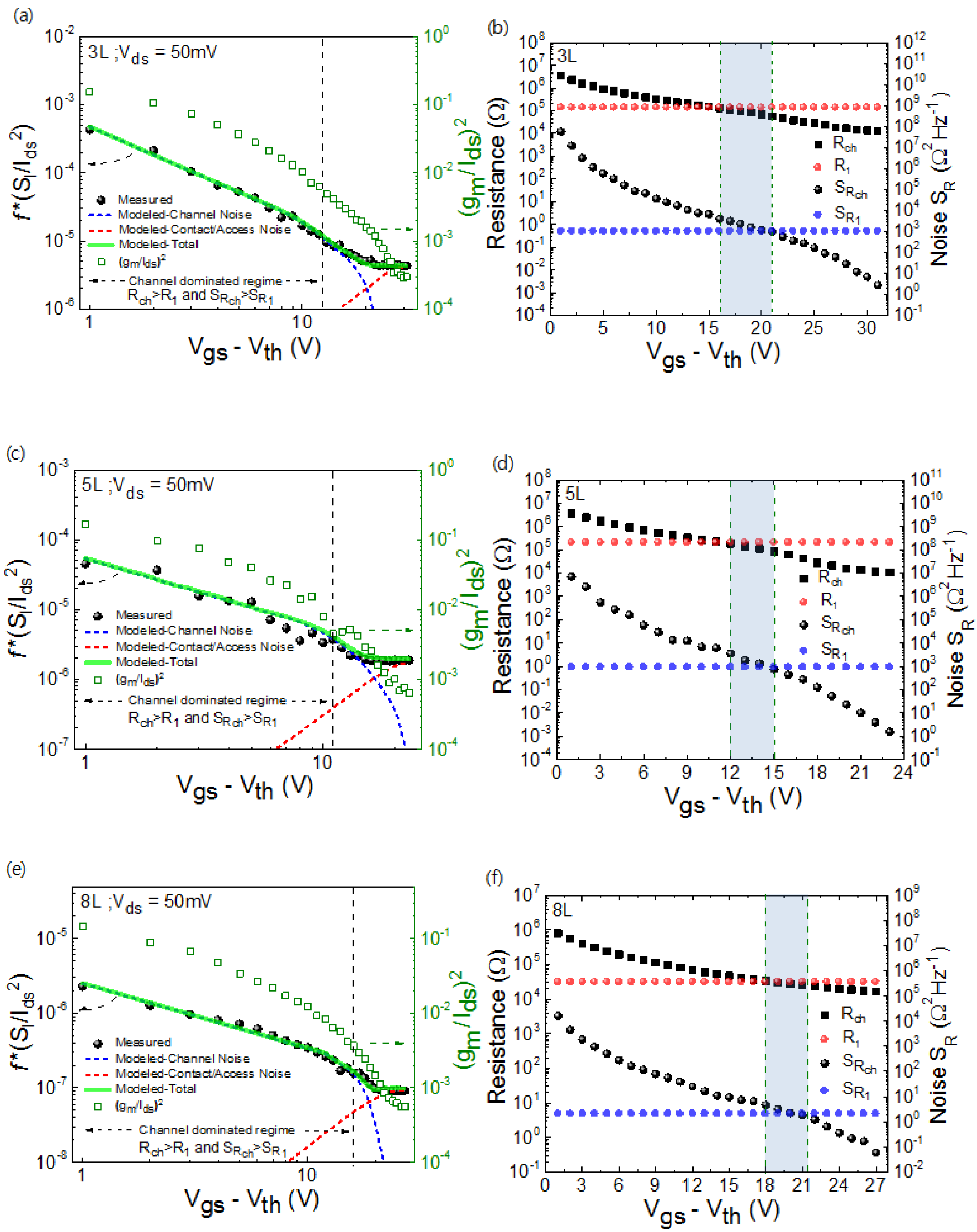


Figure C. Transconductance (g_m) as a function of the overdrive voltage (V_{gs}-V_{th}) at V_{ds}=0.2V for 15L $MoSe_2$ FET.

APPENDIX D: Noise amplitude and noise/resistance components in $MoSe_2$ FETs with various number of layers

The measured and modeled noise amplitudes are presented in this section for FETs with various layer thicknesses (15L and 40L results presented in main article). For each device, the $f*S_I/I_{ds}^2$ is shown versus (V_{gs}-V_{th}) and the resistances and noise resistance spectral power densities associated with channel and contact/access regions are presented.


(a)
3L ;Vds = 50mV
Measured
Modeled-Channel Noise
Modeled-Contact/Access Noise
Modeled-Total
(gm/Ids)2
Channel dominated regime
Rch>R1 and SRch>SR1
f*(SI/Ids2)
(gm/Ids)2
Vgs - Vth (V)
(b)
3L
Rch
R1
SRch
SR1
Resistance (Ω)
Noise SR (Ω2Hz-1)
Vgs - Vth (V)
(c)
5L ;Vds = 50mV
Measured
Modeled-Channel Noise
Modeled-Contact/Access Noise
Modeled-Total
(gm/Ids)2
Channel dominated regime
Rch>R1 and SRch>SR1
f*(SI/Ids2)
(gm/Ids)2
Vgs - Vth (V)
(d)
5L
Rch
R1
SRch
SR1
Resistance (Ω)
Noise SR (Ω2Hz-1)
Vgs - Vth (V)
(e)
8L ;Vds = 50mV
Measured
Modeled-Channel Noise
Modeled-Contact/Access Noise
Modeled-Total
(gm/Ids)2
Channel dominated regime
Rch>R1 and SRch>SR1
f*(SI/Ids2)
(gm/Ids)2
Vgs - Vth (V)
(f)
8L
Rch
R1
SRch
SR1
Resistance (Ω)
Noise SR (Ω2Hz-1)
Vgs - Vth (V)

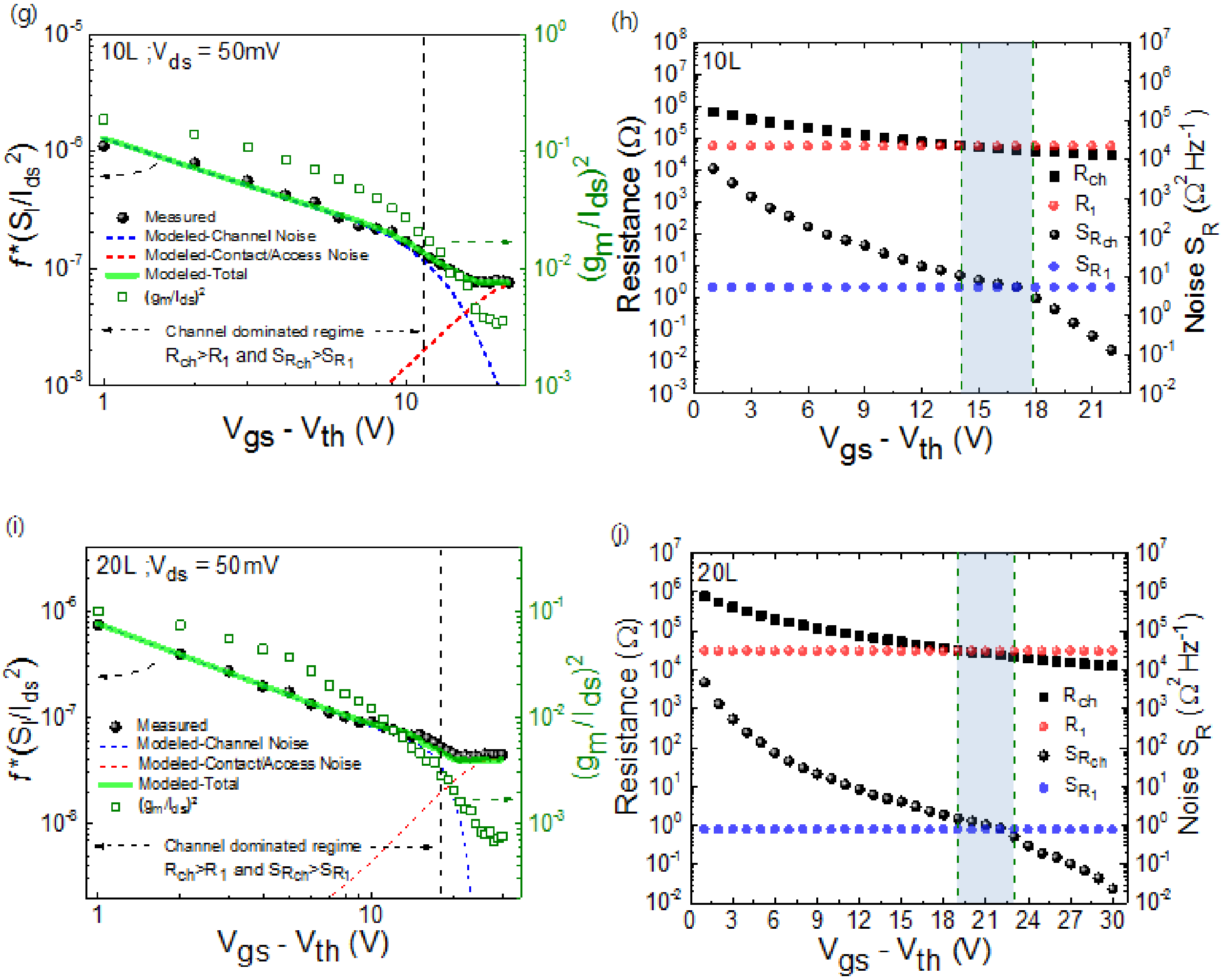


Figure D. (a), (c), (e), (g) and (i): Measured and modeled 1/*f* noise response of $MoSe_2$ FETs versus overdrive voltage. The round symbols represent the measured data points for the normalized noise current power spectral density, f^*S_I/I_{ds}^2, as a function of the gate bias. The dashed lines represent the model fitting for the corresponding noise amplitude due to noise sources in the channel (Blue) and the contact contribution (Red). The green line shows the total modeled noise amplitude (sum of the two components). Green opened square corresponds to $(g_m/I_{ds})^2$ in the right-sided y axis. (b), (d), (f), (h) and (j): Contact and channel components of the resistance noise power density and resistance for $MoSe_2$ FET, obtained from measurements using procedure described in text. Blue area represents 'transition regime’ in which channel dominates noise but contact/access regions dominate resistance. (a), (b) for 3L, (c),(d) for 5L, (e),(f) for 8L, (g),(h) for 10L and (i),(j) for 20L.

APPENDIX E: Noise amplitude and $(g_m/I_{ds})^2$ in 3L $MoSe_2$ FETs with various channel lengths

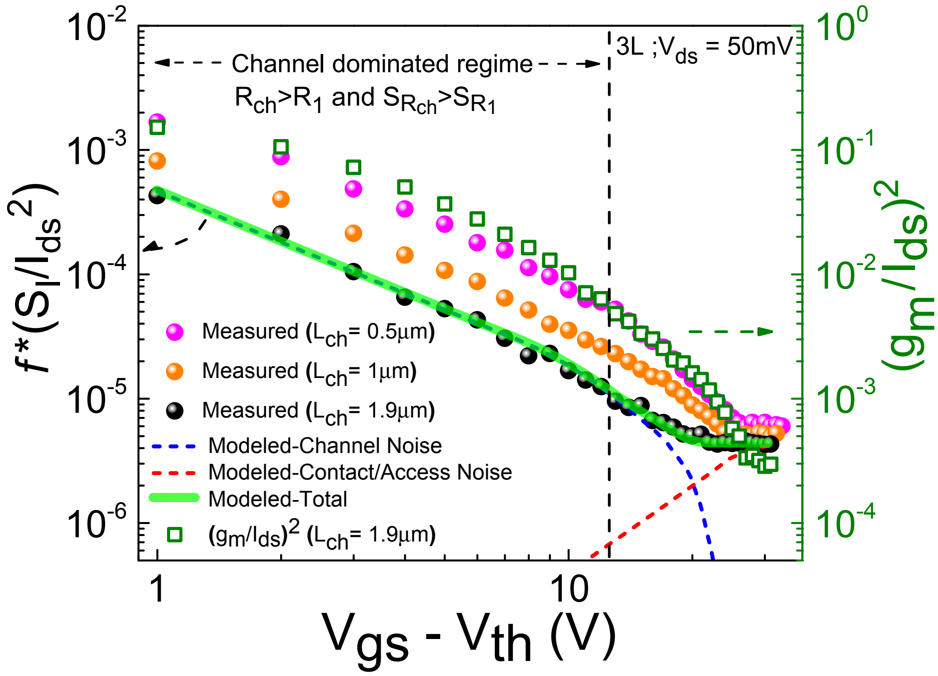


Figure E. The noise amplitudes ($f*S_I/I_{ds}^2$) and $(g_m/I_{ds})^2$ as a function of overdrive voltage in 3L $MoSe_2$ FETs. Pink, orange and black circle represent the noise amplitude of $L_{ch.}$= 0.5μm, 1μm and 1.9μm, respectively. The blue (red) dashed line indicates the model fitting for the noise in the channel (contact) regime. Green opened square corresponds to $(g_m/I_{ds})^2$. Arrows indicate the appropriate axis.

Table E. The parameters showing electrical properties and noise phenomenon in 3L $MoSe_2$ FETs with different channel lengths.

# of Layers	$L_{ch}*W_{ch}$ (μm^2)	R_1 (kΩ)	R_1*W_{ch} (kΩ*μm)	V_{th} (V)	S_{R1} [Ω^2/Hz]	α_H
3L	0.5*4	43	172	7	197.5	8.41e-1
3L	1*4	65	260	8	422	8.17e-1
3L	1.9*3	141	423	9	1014	7.08e-1

APPENDIX F: The area-dependence of noise in 3L and 8L $MoSe_2$ FETs

In order to verify that the noise amplitude scales as expected with area in the channel-dominated regime, the area dependence of noise for 3L and 8L FETs is presented in this section. Figure F shows the noise parameter multiplied by area (Area*S_I/I_{ds}^2) versus the overdrive voltage (V_{gs}-V_{th}) in 3L and 8L FETs. For each set of devices, the curves for various channel lengths are comparable in the channel-dominated regime (at the low overdrive voltages) but reach different limiting values in the contact-dominated regime (at high overdrive voltages).

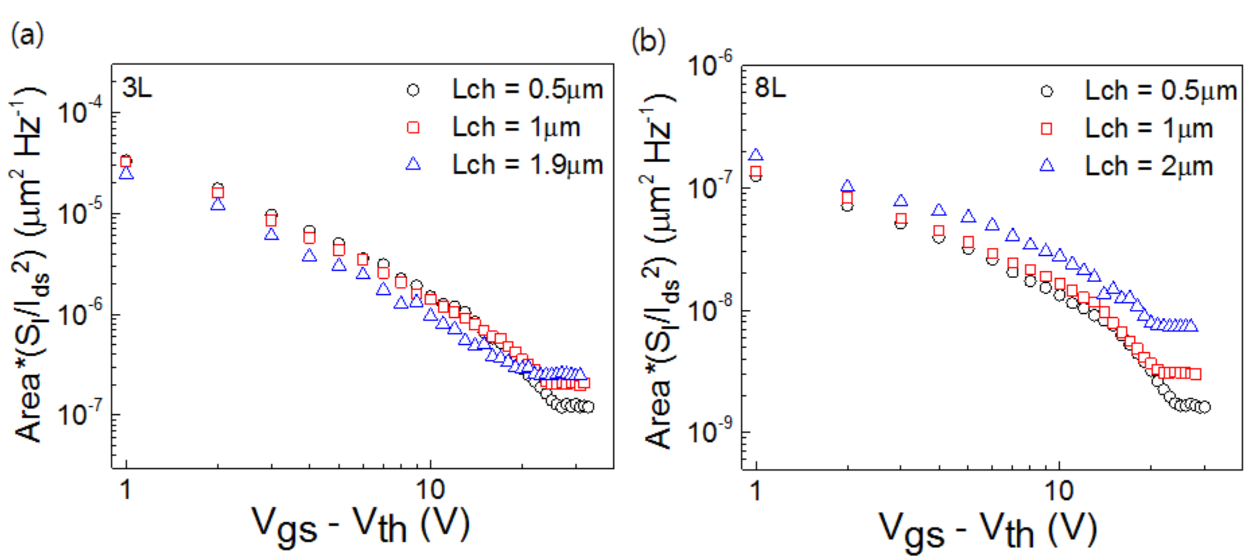


Figure F. The noise parameter (Area*S_I/I_{ds}^2) as a function of overdrive voltage in (a) 3L and (b) 8L $MoSe_2$ FETs. Black circle, red square and blue triangle represent the noise parameters of L_{ch} = 0.5μm (0.5μm), 1μm (1μm) and 1.9μm (2μm) in 3L (8L) $MoSe_2$ FETs, respectively.

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Figure captions

Figure 1. (a) A schematic view of $MoSe_2$ field-effect transistor employed in the present work. $MoSe_2$ flakes with various numbers of atomic layers were used as transistor channels. The nickel S/D contact electrodes are fabricated on top of the back-gated channel. (b) AFM image and geometrical step profile of a $MoSe_2$ flake within a representative field-effect transistor channel. The thickness of $MoSe_2$ layer is approximately 9.7nm, corresponding to ~15 layers. (c) The corresponding Raman spectrum of $MoSe_2$ flake is shown collected using a 532-nm excitation source. The presence of two principal peaks A_{1g} and E^1_{2g} confirms a bonding environment corresponding to $MoSe_2$. The inset shows the optical microscope image of the device used in this study.

Figure 2. Characteristics of $MoSe_2$ FETs with different layer thicknesses (N = 3, 5, 8, 10, 15, 20 and 40), including. (a) Transfer characteristics measured at V_{ds}=0.2V. (b) intrinsic and extrinsic field effect mobilities extracted at V_{ds}=0.2V as a function of the $MoSe_2$ layer thickness. For the 8L device, parameters are presented for the 2 μm channel length.

Figure 3. (a) 1/*f* noise current power spectral density for FETs with different number of $MoSe_2$ layers as a function of frequency for various number of layers and (b) comparison of normalized noise amplitudes (Total noise, Channel noise, Contact/Access noise) for FETs with different number of $MoSe_2$ layers. Noise measurements are performed at V_{gs}-V_{th}=7V, frequency of 100Hz and at low drain bias (V_{ds}=50mV) and channel versus contact/access contributions are extracted as described in the text.

Figure 4. (a) Measured and modeled 1/*f* noise response of 15L $MoSe_2$ FET. The round symbols represent the measured data points for the normalized noise current power spectral density, $f*S_I/I_{ds}^2$, as a function of the gate bias. The dashed lines represent the model fitting for the noise dominated by the channel contribution and the contact contribution, respectively. The green line shows the sum of both contributions. Green opened square corresponds to $(g_m/I_{ds})^2$ in the right-sided y axis. The agreement between the modeled fitting and measured data indicates that the measured voltage dependence can be explained by a channel following Hooge's mobility fluctuation model, with a transition to contact/access dominated regime. (b) Contact and channel components of the noise and resistance for 15L $MoSe_2$ FET, obtained from measurements using procedure described in the text. Blue area represents 'transition regime' in which channel dominates noise but contact/access regions dominate resistance. (c) Measured, modeled 1/*f* noise response and $(g_m/I_{ds})^2$ of 40L $MoSe_2$ FET, using same symbols as (a). (d) Contact and channel components of the noise and resistance for 40L $MoSe_2$ FET, using same symbols as (b). In comparison to 15L FET, the transition voltages are lower, and the width of the transition region is smaller. The noise amplitudes of the channel-dominated regime (at same bias point) and the contact/channel dominated regime are also larger, corresponding to a larger Hooge parameter and an increased noise contribution from interlayer resistances, respectively.

Figure 5. The noise amplitudes ($f*S_I/I_{ds}^2$) and $(g_m/I_{ds})^2$ as a function of overdrive voltage in 8L $MoSe_2$ FETs. Pink, orange and black circle represent the noise amplitude of L_{ch}=0.5μm, 1μm and 2μm, respectively. The blue (red) dashed line indicates the model fitting for the noise in the channel (contact) regime. Green opened square corresponds to $(g_m/I_{ds})^2$. Arrows indicate the appropriate axis.

Figure 6. Comparison of noise parameters at 10V overdrive voltage (a) The comparison of normalized noise amplitudes (Total, Channel, Contact/Access) for FETs with different number of $MoSe_2$ layers. All the noise measurements are performed at V_{gs}-V_{th}=10V, frequency of 100Hz and low drain bias (V_{ds}=50mV). (b) Hooge's constants (α_H) as a function of number of layers in $MoSe_2$ FETs. The inset shows schematic representation of the intrinsic and extrinsic FETs. (c) Representation of total noise originating from three independent current noise sources, namely, contact resistance, interlayer coupling resistance, and the channel resistance. (d) Thevenin equivalent resistance noise sources are shown.

Table 1. The electrical transport parameters and noise parameters of $MoSe_2$ field-effect transistors with various channel thicknesses studied in this work.

# of Layers	V_{th}	L_{ch}(μm) x W_{ch}(μm)	R_1[KΩ]	R_1*W_{ch}[Ω*mm]	S_{R_1} [$Ω^2$/Hz]	$α_H$	Voltage of Cross Point (1^{st} and 2^{nd} terms)
3L	9V	1.9*3	141	423	1014	7.08e-01	20V
5L	17V	2*1.8	210	378	925.5	2.61e-01	17V
8L	10V	0.5*3	12	36	0.33	9.83e-03	22V
8L	12V	1*3	20	60	0.82	9.24e-03	20V
8L	13V	2*4	32	128	2.09	9.47e-03	19V
10L	18V	1.9*2.1	54.2	113.8	5	5.25e-03	16V
15L	13V	2*1.8	21	37.8	0.275	2.64e-03	19V
20L	10V	2*1.9	30	57	0.77	4.58e-03	20V
40L	11V	1.8*2.2	187	411	137	1.54e-02	9V

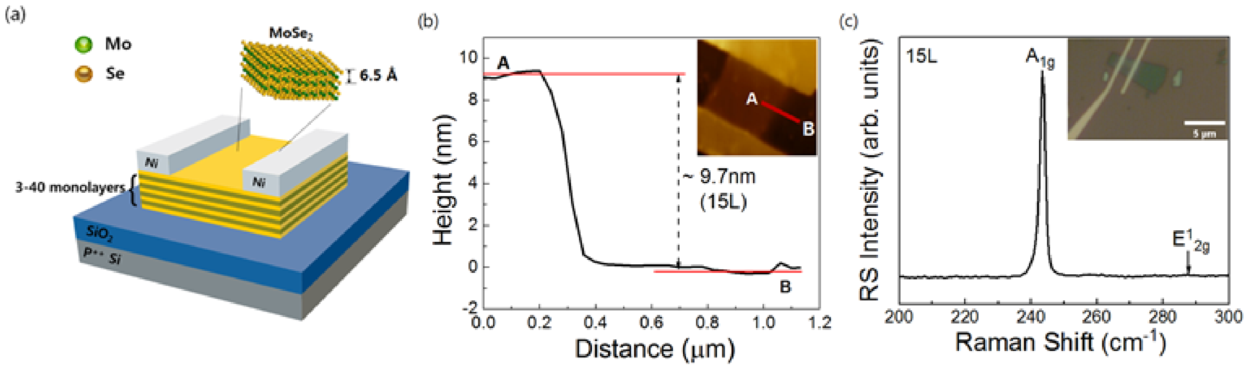
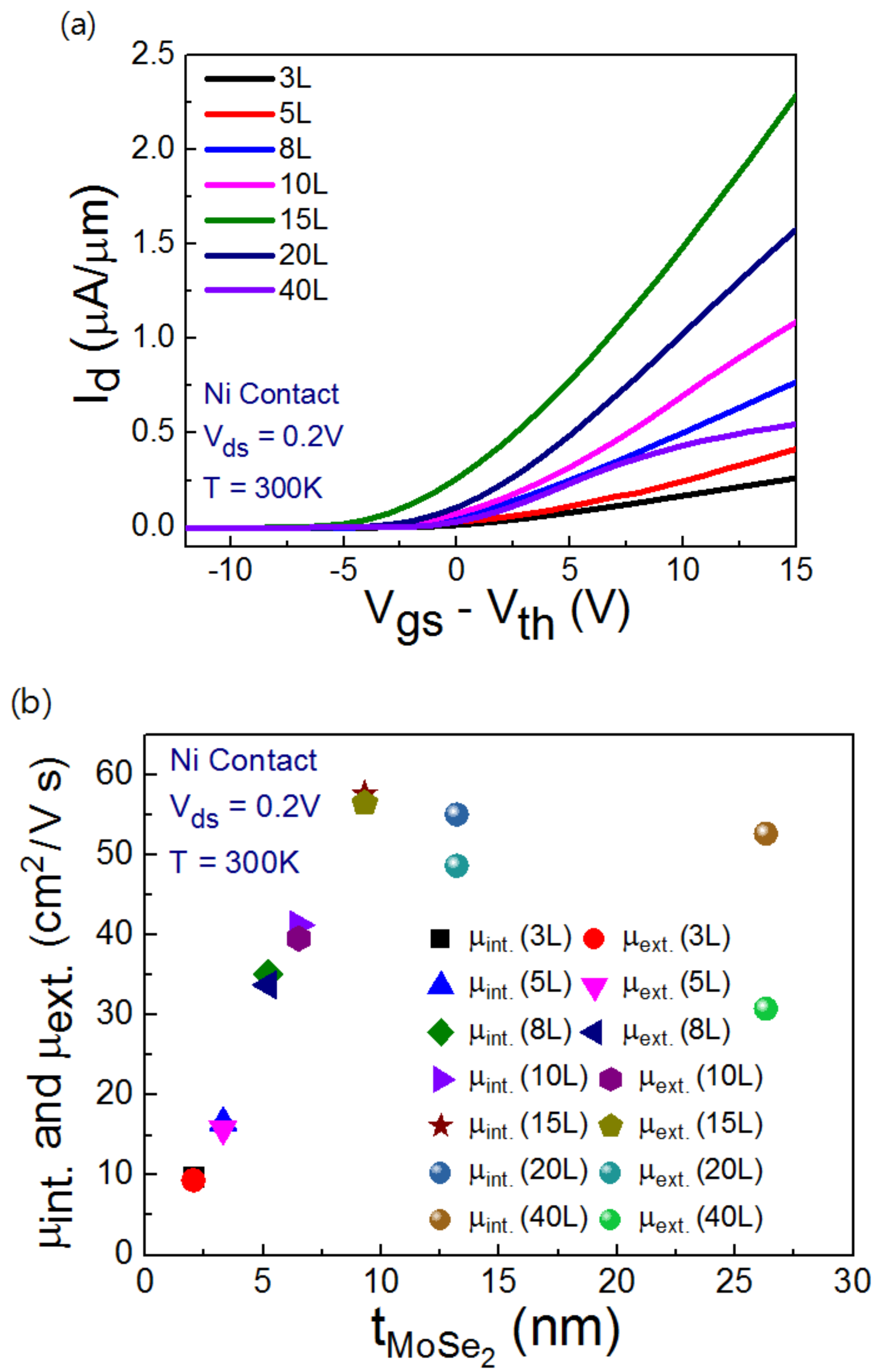


Figure 1. *Kwon et al*



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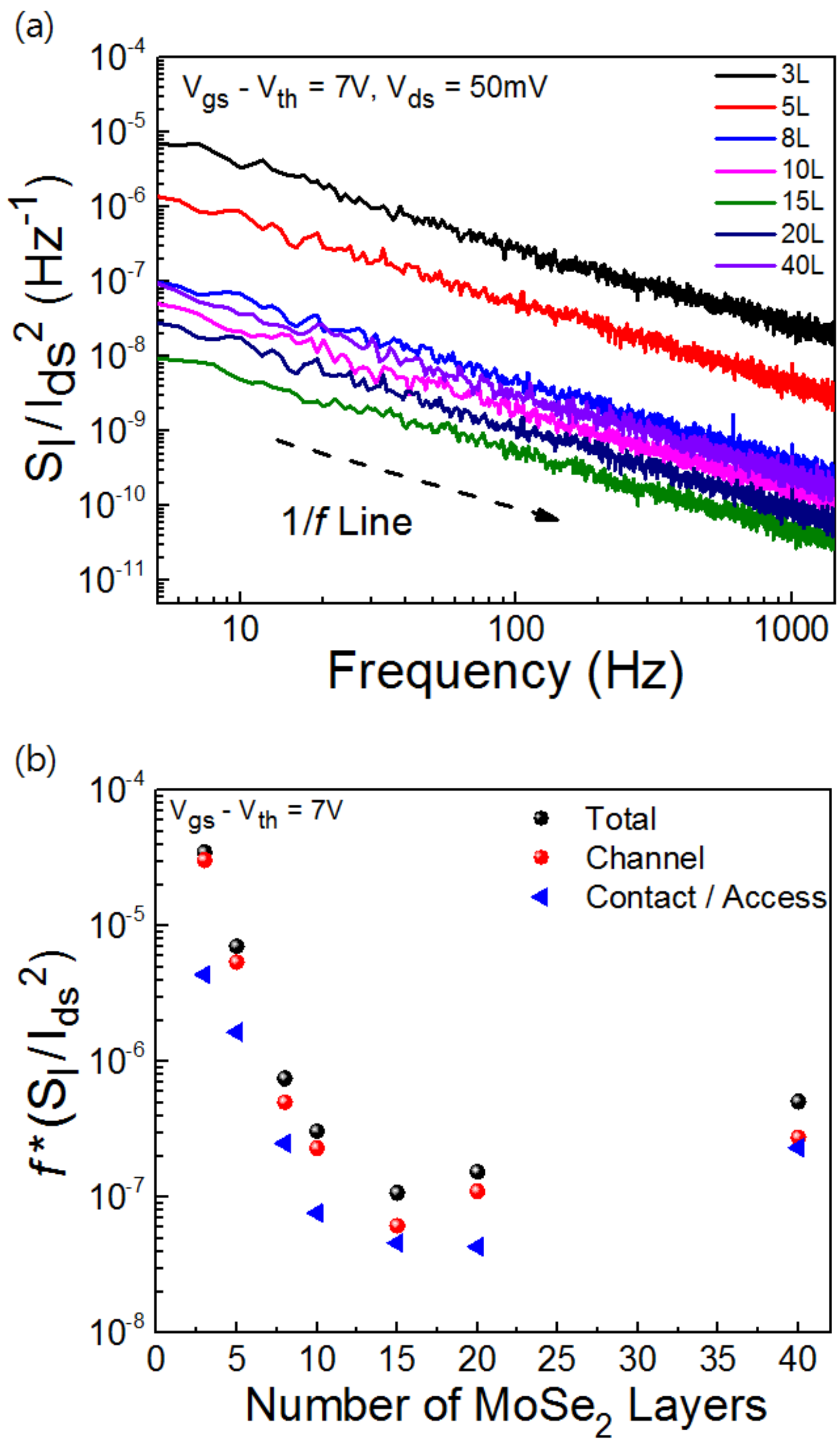

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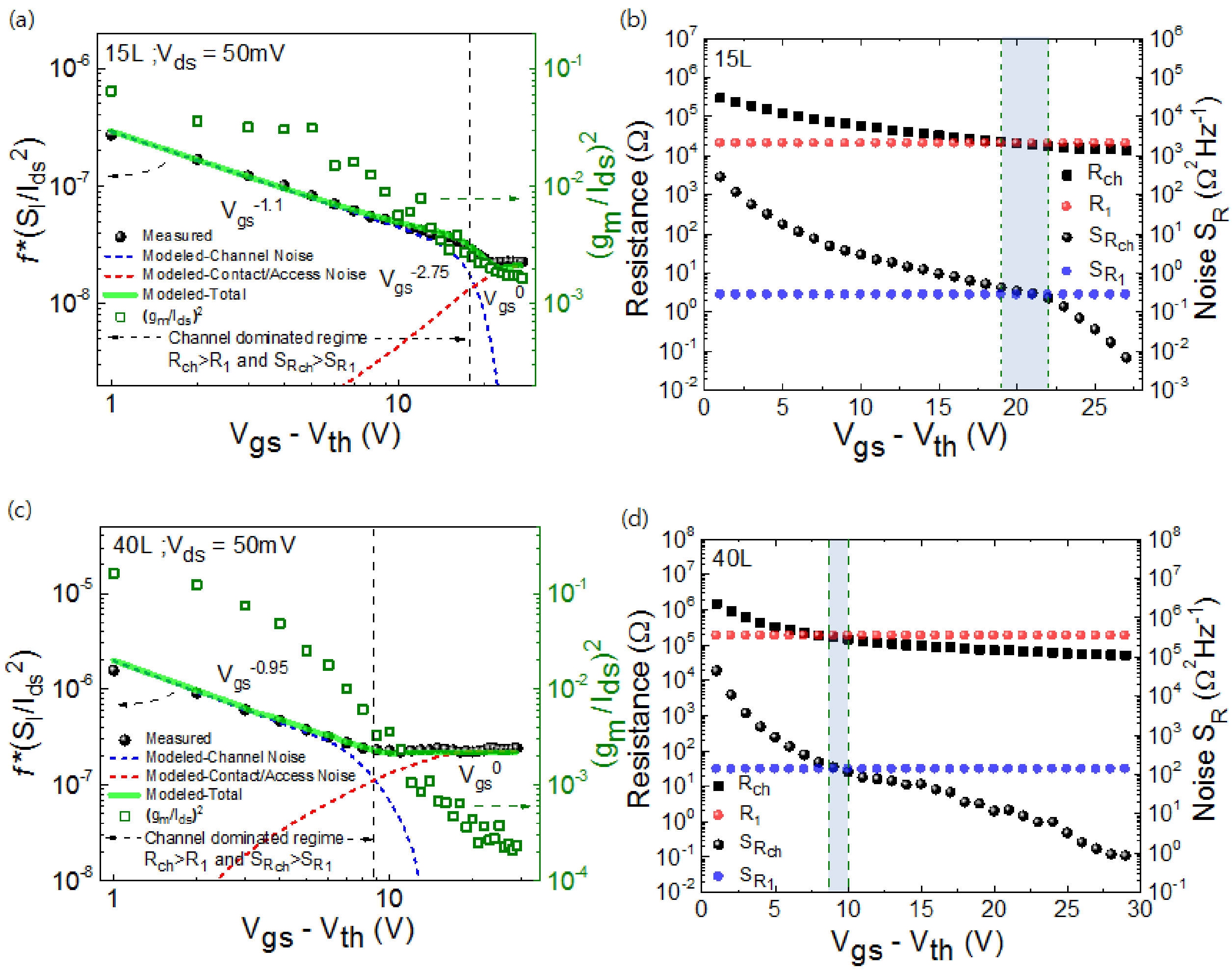

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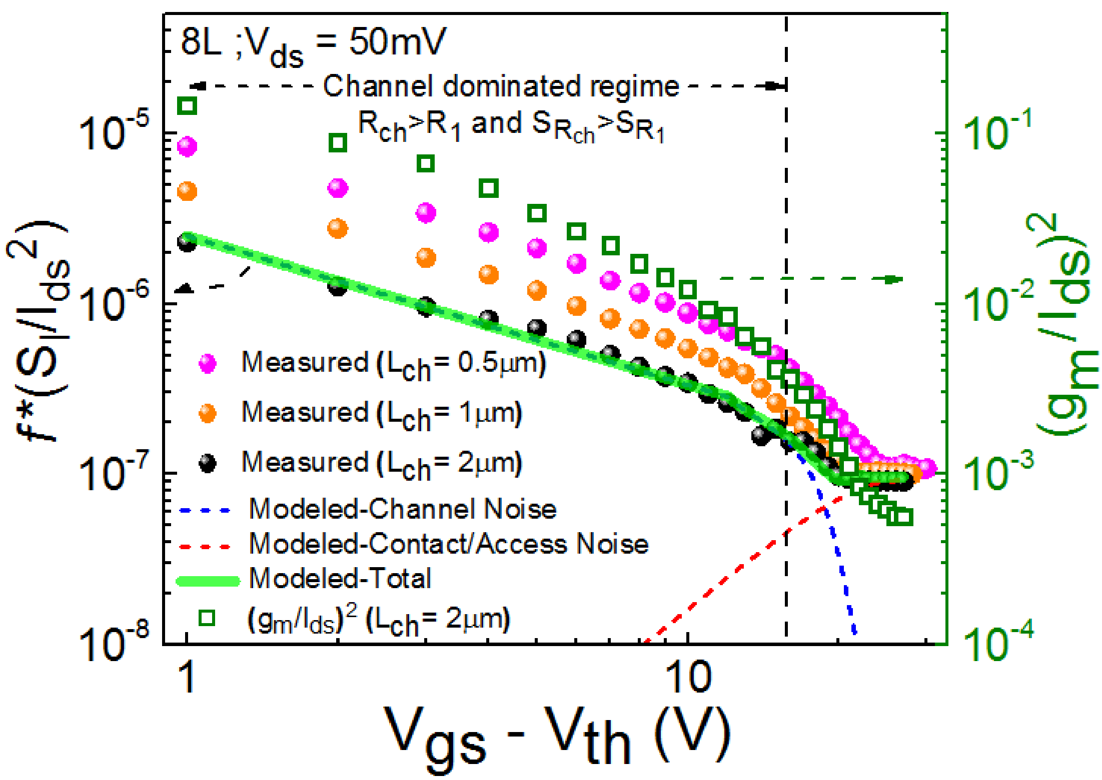

Figure 5. *Kwon et al*

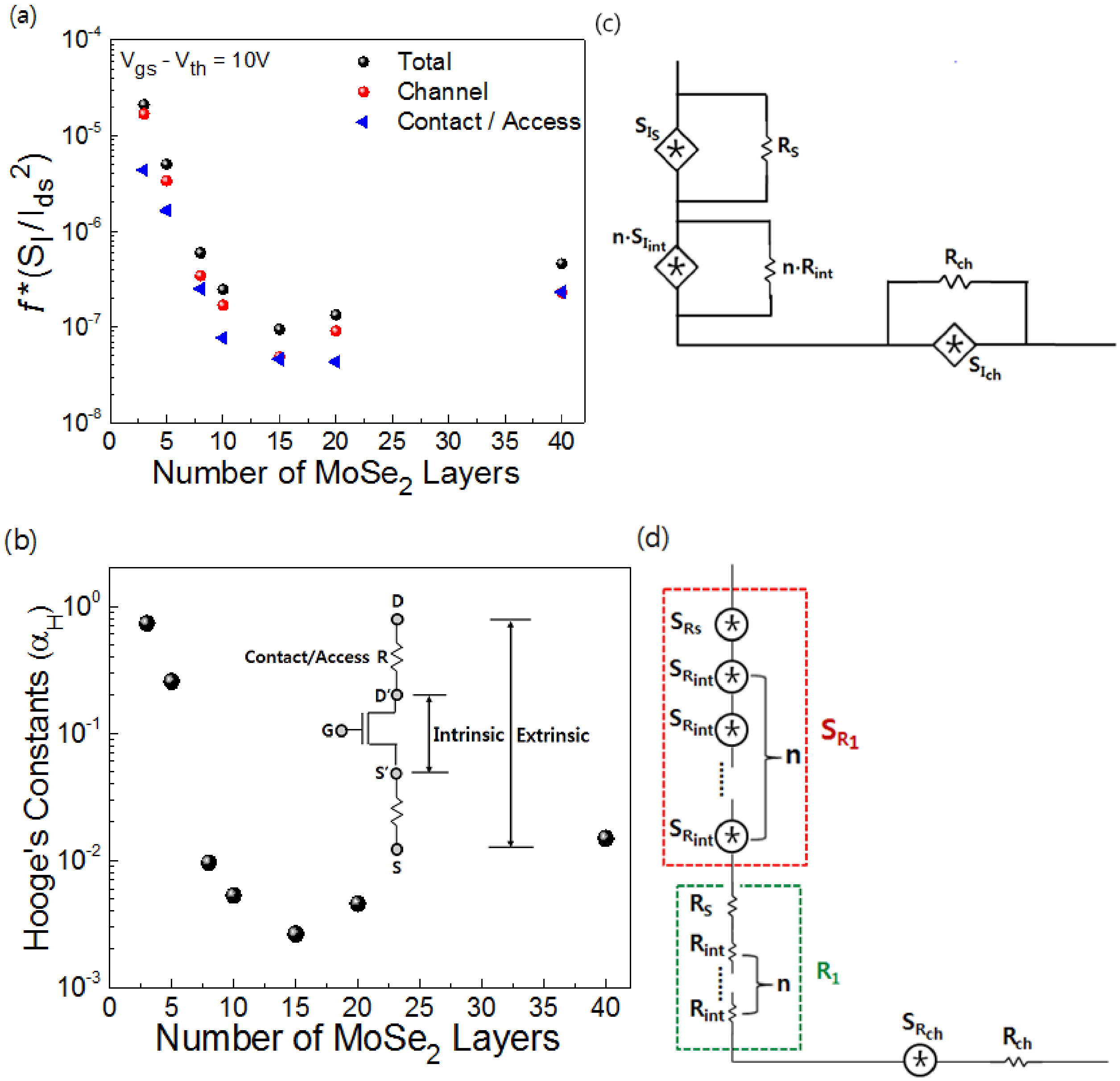

Figure 6. *Kwon et al*