Percolative switching in transition metal dichalcogenide field-effect transistors at room temperature

Tathagata Paul, Subhamoy Ghatak and Arindam Ghosh

Department of Physics, Indian Institute of Science, Bangalore 560012, India

E-mail: tathagata@physics.iisc.ernet.in and arindam@physics.iisc.ernet.in

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Abstract

We have addressed the microscopic transport mechanism at the switching or ‘on–off’ transition in transition metal dichalcogenide (TMDC) field-effect transistors (FETs), which has been a controversial topic in TMDC electronics, especially at room temperature. With simultaneous measurement of channel conductivity and its slow time-dependent fluctuation (or noise) in ultrathin WSe2 and MoS2 FETs on insulating SiO2 substrates where noise arises from McWhorter-type carrier number fluctuations, we establish that the switching in conventional backgated TMDC FETs is a classical percolation transition in a medium of inhomogeneous carrier density distribution. From the experimentally observed exponents in the scaling of noise magnitude with conductivity, we observe unambiguous signatures of percolation in a random resistor network, particularly, in WSe2 FETs close to switching, which crosses over to continuum percolation at a higher doping level. We demonstrate a powerful experimental probe to the microscopic nature of near-threshold electrical transport in TMDC FETs, irrespective of the material detail, device geometry, or carrier mobility, which can be extended to other classes of 2D material-based devices as well.

Keywords: percolative transport, 1/f noise, TMDC FET

(Some figures may appear in colour only in the online journal)

1. Introduction

The expanding family of atomically thin layers of semiconducting transition metal dichalcogenide (TMDC) materials for electronic [1–7], optoelectronic [8–14], valleytronic [15–19], and even piezoelectronic [20] applications, has defied a generic framework of electron transport because of diverse material quality, channel thickness-dependent band structure, dielectric environment, and the nature of substrates. A wide variety of physical phenomena ranging from variable-range hopping [5], metal–insulator transition [7] to classical percolative charge flow through an inhomogeneous medium [21, 22] were reported for MoS2, the implications of which often lead to a conflicting microscopic scenario. At low carrier density, for example, hopping via single particle states trapped at short-range background potential fluctuations (approximately a few lattice constants [23]) is incompatible with the observation of classical percolative conduction that requires long-range inhomogeneity in the charge distribution, created when linear screening of the underlying charge disorder breaks down [24–27]. Observations of metal–insulator transition [7, 22] have added to this controversy with both many-body Coulomb interaction as well as classical percolation transition being argued as possible driving mechanisms. With the emergence of new TMDC-based field-effect transistors (FETs), in particular, WSe2 [19, 28–35], WS2 [36–39], and MoTe2 [6], the importance of a generic probe for the microscopic details of density (or gate-voltage-) dependent charge distribution that affect the mobility, subthreshold slope, and other performance markers in TMDC electronics, is paramount.
Unlike variable-range hopping in the strongly localized regime, however, identifying charge percolation in FET channels is less straightforward. Theoretically, classical percolation-limited conductivity in metal–insulator composites is characterized by established critical exponents [21, 24, 25, 40–44], but the experimental difficulty lies in accurately determining the fraction \( p \) of the conducting region, or ‘puddles,’ embedded inside the insulating matrix. Hence, despite compelling evidence of long-range inhomogeneity in the charge distribution in MoS\(_2\) FETs [21, 22], its manifestation in transport remains indirect and confined only to low temperatures. A way to circumvent this difficulty involves measuring the low-frequency noise or \( 1/f \) noise in the channel conductivity \( \sigma \), which also scales with \( p \) with independent characteristic scaling exponents [40, 42], and diverges at the percolation threshold (\( p_c \)) [41]. A direct relation between normalized noise magnitude \( N_p \) and \( \sigma \), thus, eliminates the necessity to know either \( p \) or \( p_c \) accurately. In such a case,

\[
N_p = \frac{\langle \delta \sigma^2 \rangle}{\sigma^2} \propto \sigma^{-\nu},
\]

where the scaling exponent \( \nu \) assumes universal values depending on the nature of the percolation. In the 2D lattice models of a random resistor network (RR), for example, \( \nu \approx 0.86 \) or 1.5 [40, 45], whereas in the continuum percolation framework, such as the ‘swiss-cheese model’ [44], \( \nu \approx 3.2 \) for random void (RV), insulating voids in a conducting background) and \( \approx 0.87 \) for inverted RV (IRV), weakly connected conducting regions in an insulating matrix), respectively [41, 42]. In this work, we have investigated the switching process in TMDC FETs by simultaneously measuring \( N_p \) and \( \sigma \) as the electrical transport is tuned from the strongly insulating to the quasi-metallic regime using a gate voltage. While noise in all devices was found to primarily originate from carrier number fluctuations at the channel-substrate interface, the key result is the observation of an unambiguous scaling of \( N_p \) with \( \sigma \), suggesting classical percolation in a spatially inhomogeneous medium at the onset of conduction. Similar behaviors for both WSe\(_2\) and MoS\(_2\) FETs imply that percolative switching could be generic to backgated TMDC FETs, irrespective of material and device-related parameters.

We chose WSe\(_2\) FETs as the primary experimental platform for the following reasons: first, WSe\(_2\) is an emerging TMDC FET material with several desirable properties ranging from high carrier mobility due to low effective mass of the carriers, ambipolar conduction, and superior chemical stability compared to sulfides [12, 13, 28, 32, 33, 35, 37]. Second, despite the progress in standard electrical transport properties [19, 28–35], the origin and magnitude of the intrinsic \( 1/f \) noise, a crucial performance limiting factor in electronic device applications, in WSe\(_2\) FETs are not known, and third, given the recent studies of noise in MoS\(_2\) FETs [46–50], similar studies in WSe\(_2\) allow identification of the generic aspects of noise processes in TMDC FETs, which, in turn, provides crucial insight into the microscopic details of charge distribution and disorder.

2. Results and discussions

The experiments were carried out in FETs fabricated from ultrathin films of WSe\(_2\) (and MoS\(_2\)) obtained via mechanical exfoliation on \( p^{+}-\text{Si}/(285\text{ nm})\text{SiO}_2 \) substrates in the conventional backgated geometry (schematic and typical device image in figure 1(a)) (details of the measurement technique are provided in the supplementary information). The details of the devices can be found in table 1. In order to verify that the structural integrity of the WSe\(_2\) channels were unaffected by the device fabrication process, we carried out Raman spectroscopy on, (1) the original block of WSe\(_2\) that was subsequently mechanically exfoliated to form the device WSeML\(_2\), (2) the channel region prior to device fabrication, and (3) the same after device fabrication. The normalized Raman spectra (figure 1(b)) remain essentially unchanged with characteristic Raman modes for multilayer WSe\(_2\) including those at \( \approx 247.3 \ (E^{\text{1}}) \), \( \approx 249.5 \ (A_1^\text{g}) \) and \( \approx 308.5 \ \text{cm}^{-1} \ (A_2^\text{g}/A_2^\text{l}) \) [51], implying no detectable structural damage due to the exfoliation or the device fabrication processes. Similar characteristics for the MoS\(_2\) channels and detailed surface characterization with atomic force microscopy can be found in the supplementary material. Measurement of both standard transport and noise were performed in a two-probe geometry via an ac lock-in amplifier technique where the latter was recorded by digitizing the amplifier output by an analog-to-digital converter over a bandwidth of \( \approx 0.01 – 10 \text{ Hz} \) [47].

In TMDC FETs, thermal annealing and environmental exposure have drastic effects on electrical mobility, threshold voltage, and other parameters [35, 37, 52]. Recently, we have shown [47] that thermal annealing can also reduce the noise magnitude in MoS\(_2\) FETs by over two orders of magnitude, through improved transparency of the electrical contacts [37, 52]. We found a strong effect of annealing on the electrical transport in our WSe\(_2\) FETs. In figures 1(c)–(f), we illustrate the effect of annealing on both transport and noise characteristics in WSe\(_2\) FETs as well as the sensitivity of these parameters to environmental contamination. The inset of figure 1(c) shows the dependence of the source-drain current (\( I_{\text{sd}} \)) on gate voltage \( V_g \) in device WSeML\(_2\) under three conditions: (a) in air/atmosphere prior to annealing (labeled as Air), (b) in vacuum (\( \approx 10^{-5} \text{ mbar} \)) prior to annealing (labeled as Vacuum), and (c) after 1 h of annealing at 400 K (in vacuum) (labeled as Vac. Anneal). The annealing conditions were kept the same for all WSe\(_2\) and MoS\(_2\) devices reported here. Apart from the evident increase in \( I_{\text{sd}} \) on annealing, typically to about \( \sim 100 \text{ nA} \) at the largest experimental \( V_g \) (figure 1(c)) (\( V_{\text{sd}} = 100 \text{ mV} \)), we also note: (i) First, a shift in the turn-on voltage \( V_{\text{ON}} \) indicated by the dashed vertical lines, towards negative values. This had been observed earlier in WSe\(_2\) [37] and MoS\(_2\) [53] channels and implied desorption of gas and water dopants. (Here, \( V_{\text{ON}} \) is calculated by extrapolating the \( \sqrt{I_{\text{sd}}} \) versus \( V_g \) plot in the ON state of the transistor and finding its intercept on the \( V_g \) axis [54].) This makes \( p \)-type conduction in our WSe\(_2\) channel inaccessible within the experimental range of \( V_g \), although it allows a wide operating range in the \( n \)-doped regime. (ii)
Second, nearly four decades of increase in the FE mobility (\( \mu = (1/C_{ox})\sigma \partial V_g \partial V_d \), where \( C_{ox} \) is the gate capacitance per unit area) (figure 1(d)) to \( \mu \approx 0.5 - 5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \), in agreement with previous reports [37], although smaller than boron nitride encapsulated WSe\(_2\) channels [55–57]. (iii) Third, linear and symmetric \( I_d \) vs \( V_d \) characteristics at low source-drain voltages (up to \( |V_d| \leq 100 \text{ mV} \)) (supplementary material), confirming the ohmic nature of the contacts. All electrical measurements were limited to the linear transport regime where the fluctuations in \( I_d \) reflects that of \( \sigma \). Thermal annealing in vacuum had a dramatic effect on the intrinsic low-frequency \( 1/f \)-noise magnitude in WSe\(_2\) FETs, particularly, at large values of \( V_g \) (high doping). This is illustrated in the upper inset of figure 1(e), which shows the normalized time-dependent current fluctuations \( \partial I_d / I_d \) at the same gate bias before and after the annealing process. The overall shape

Figure 1. Device structure and transport characterization. (a) Device schematic and optical micrograph of a typical WSe\(_2\) FET. (b) Raman spectra for bulk WSe\(_2\), WSe\(_2\) flakes after exfoliation (prefabrication) and following device processing (postfabrication). (c) Transfer characteristics of three WSe\(_2\) FETs after annealing. The dashed lines indicate the turn-on voltage (see text). (Inset) A comparison of the transfer characteristics in air (labeled ‘Air’), in vacuum before annealing (labeled Vacuum), and in vacuum after annealing (labeled ‘Vac. Anneal’) for the device WSeML\(_2\). (d) Comparison of the FE mobility before (BA) and after (AA) annealing curves for three devices WSeML\(_2\), WSeML\(_3\), and WSeBL. (e) Normalized power spectral density of current fluctuation showing a \( 1/f^\alpha \)-type frequency dependence. Lower inset: \( V_d \) dependence of frequency exponent \( \alpha \) both BA and AA. A large reduction in the normalized time-dependent current fluctuations is observed after annealing (upper inset). (f) Comparison of normalized noise magnitude \( S_{1/f} \) for WSeML\(_2\) BA and AA as a function of gate voltage \( V_g \) measured from the turn-on voltage \( V_{ON} \). Inset: area-scaled normalized noise magnitude after annealing for two devices WSeML\(_2\) and WSeML\(_3\).
of the power spectral density $S(f)$ of the fluctuations depends on frequency $f$ as $S(f) \propto 1/f^{\alpha}$ with $\alpha \approx 1$ (figure 1(e)). Similar power spectra of noise are commonly observed in electronic channels of 2D materials, such as graphene [58–62], topological insulators [63, 64], and TMDCs [46–48, 65, 66]. We find that annealing leaves the exponent $\alpha$ largely unaffected (lower inset of figure 1(e)) but strongly modifies the $V_g$ dependence of normalized noise magnitude $S/f^\alpha$ as shown in figure 1(f) with the data from device WSeML_2. The preanneal $V_g$ dependence of $S/f^\alpha$ is weak with a monotonic decrease as $V_g$ is increased, whereas, the variation in $S/f^\alpha$ becomes nonmonotonic after annealing and can be smaller than the preanneal noise by more than two orders of magnitude at large $V_g$ [47, 65]. Quantitatively, the total measured noise can be decomposed into noise from the contact (normalized noise $x_{\text{con}}$) and the channel (normalized noise $x_{\text{ch}}$) regions so that $S/f^\alpha = \eta^2 x_{\text{con}} + (1 - \eta)^2 x_{\text{ch}}$ with $\eta = G_{\text{ch}}/(G_{\text{ch}} + G_{\text{con}})$, where $G_{\text{ch}}$ and $G_{\text{con}}$ are the channel and the contact conductances, respectively [46]. Prior to annealing, $\eta \approx 1$, and the contact noise is expected to dominate, while the postannealing ($\eta < 10^{-4}$) noise is determined by the channel region. The weak gate voltage dependence of noise before annealing suggests a gate-voltage-independent tunnel barrier at the metal–TMDC interface. This could be due to the condensation of water, polymethyl methacrylate residues, etc., as reported previously [37]. We have also examined the dependence of the postannealed noise magnitude on the channel area ($A$) of two devices of different sizes from the same WSe2 flakes. As shown in the inset of figure 1(f), $A \propto S/f^\alpha$ from the devices collapse at all $V_g$, implying $S/f^\alpha \propto 1/A$, which is expected when noise originates from the channel region [67]. (The $1/A$ dependence was not observed in the preannealed noise.) In the remainder of this paper, we have confined our discussion only to the postanneal noise behavior in the TMDC channels. Moreover, in order to analyze the noise data without referring to any specific frequency, we have computed the ‘variance’ of the integrated power spectral density as $N_v = \langle \delta \sigma^2 \rangle /\langle \sigma^2 \rangle = (1/|I_{\alpha}|^2) \int S(f) df$ where the integration was carried out within the experimental bandwidth.

In order to explore the microscopic mechanism of noise in WSe2 FETs, we note the strong peak close to the steepest rise in the $I_{\alpha} - V_g$ transfer characteristics at a device-dependent gate voltage $V_g^\ast$ in all WSe2 FETs (figure 2). This naturally suggests the noise from McWhorter (MCW) carrier number fluctuations [68] where the fluctuation in $I_{\alpha}$ is due to the trapping and detrapping of free carriers at the channel-oxide interface. This is equivalently represented by the flat-band gate-voltage fluctuations and, thus, resulting in current noise being proportional to the transconductance $g_m = \partial I_{\alpha}/\partial V_g$ of the channel. To establish this quantitatively, the noise magnitude can be written as [46–50, 68]

$$N_{\text{MCW}} = \langle \delta I_{\alpha}^2 \rangle /|I_{\alpha}|^2 = \frac{6.2e^2k_BT}{Ae^{2\xi}} D_0 g_{m}^2 |I_{\alpha}|^2, \quad (2)$$

where $D_0 \approx 10^{18} - 10^{20}$ eV$^{-1}$ cm$^{-3}$ is the density of trap states in SiO2 and $n^\ast \approx 10^9$ m$^{-3}$ is the inverse of the electronic wave function decay scale inside the oxide. Using $D_0$ as the fitting parameter and experimentally determined $g_{m}$, we have compared the $V_g$ dependence of the observed noise magnitude $N_v$ and that expected from the MCW model (equation (2)) for all WSe2 FETs (figure 2). The excellent agreement with realistic range of values of $D_0$ for SiO2 establishes the carrier number fluctuations at the channel-SiO2 interface as the predominant source of noise in our WSe2 FETs.

Subsequently, we have examined the dependence of $N_v$ on the channel conductivity $\sigma$, which shows very similar trends for all three WSe2 devices. In figures 3(a), (c), (d), three distinct regions can be clearly identified: (i) Region I: The low-conductivity regime at $V_g < V_g^\ast$, where $N_v$ increases from a finite value with increasing $\sigma$ (dashed lines) to the maximum at $V_g^\ast$ that corresponds to $\sigma \approx 3 - 5 \times 10^{-8}$ S/\Ohm, (ii) Region II: at $V_g^\ast \approx V_g^\ast$ extending over $\sigma \approx (0.5 - 3) \times 10^{-7}$ S/\Ohm (indicated as the shaded area in figures 3(a)–(d)) where $N_v \propto \sigma^{-(1.5 \pm 0.2)}$, and (iii) Region III at $V_g^\ast > V_g^\ast$ and $\sigma \approx 3 \times 10^{-7}$ S/\Ohm, where $N_v$ decreases rapidly as $N_v \propto \sigma^{-(3.1 \pm 0.3)}$. The three regimes are characterized by distinct $T$ dependences of $\sigma$ as illustrated for WSeML_2 in figure 3(b), although other devices show very similar behavior (supplementary material) [35, 37, 52]. The weak $T$ dependence of $\sigma$ in Region III signifies a disordered quasimetallic regime with weakly localized electron transport. In Regions I and II, i.e., around the switching transition ($\sigma \lesssim 10^{-7} - 10^{-8}$ S/\Ohm), the insulating behavior becomes progressively stronger with decreasing $V_g$, although the signature of variable-range hopping develops only at much lower $V_g$, i.e., stronger localization (see figure 3(b) and supplementary material for more details), which makes identifying the transport mechanism at switching from $T$ dependence of $\sigma$ alone a very difficult task.

The exponents $\nu$ in $N_v \propto \sigma^{1+\nu}$ scaling, however, provide direct evidence of a percolative transport with the noise peak signifying the percolation threshold at $V_g \approx V_g^\ast$ [40, 42, 69]. Below the percolation threshold ($V_g < V_g^\ast$; Region I), called

| Device name | $L$ ($\mu$m) | $W$ ($\mu$m) | Contact details | No. of layers |
|-------------|-------------|-------------|----------------|--------------|
| WSeML_2     | 2.8         | 3           | Ti/Au 10 nm/50 nm | 5            |
| WSeBL       | 1.5         | 5.3         | Ti/Au 10 nm/50 nm | 2            |
| WSeML_3     | 1.8         | 3           | Ti/Au 10 nm/50 nm | 5            |
| MoSSL       | 3           | 4           | Cr/Au 10 nm/50 nm | 1            |
| MoSSL_1     | 0.876       | 0.861       | Cr/Au 10 nm/50 nm | 1            |
| MoSSL_2     | 0.562       | 1.023       | Cr/Au 10 nm/50 nm | 1            |
the ‘dielectric regime,’ transport occurs by hopping or tunneling through disconnected metallic puddles [70] and approaches a finite device-dependent magnitude at low $V_g$ away from the threshold. In the critical (metallic) regime immediate to the percolation threshold ($V_g \gtrsim V_g^c$: Region II), $\nu \approx 1.5$ corresponds to percolation in the random resistor (RR) network (figure 3(e)) with a broad distribution of intersite resistance [40]. On further increase in $V_g$, the crossover to $\nu \approx 3$ in Region III marks the onset of continuum percolation with random voids, signifying transport in the delocalized Fermi sea in the presence of insulating islands [42]. At higher conductivities ($\sim 10^{-6} \text{ S/cm}$) the noise reduces further, suggesting a breakdown of the percolation scenario. A similar variation of $\nu$, and thereby the nature of percolative transport, has been observed earlier in a number of metal—insulator composites with varying fraction of the metallic component (see, for example, [69]). In our case, it allows a unique route to monitor the evolution of carrier distribution with gate voltage, or Fermi energy, especially at switching. Switching by percolation transition within the

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**Figure 2.** Integrated noise and number fluctuation. Plots of integrated power spectral density (markers), calculated MCW noise $N_{MCW}$ (olive green colored line) using substrate trap density $D_{it}$ as the fitting parameter (equation (2)) and source drain current (navy blue line) for (a) WSeBL, (b) WSeML_2, (c) WSeML_3. The remarkable agreement between the calculated MCW noise with the experimental noise magnitude indicates channel carrier number fluctuations as the source of flicker noise in our WSe_2 channels.

**Figure 3.** Noise-conductivity scaling and percolation. Dependence of noise magnitude $N_{\sigma}$ on conductivity $\sigma$ and the gate-voltage dependence of $\sigma$ (insets) for (a) WSeML_2, (c) WSeML_3, (d) WSeBL. Different noise scaling regimes are indicated by solid lines with respective exponents ($\nu$). The shaded region outlines the transition region with $\nu = 1.5$. (b) Temperature dependence of $\sigma$ of WSeML_2 indicating transition from localized to an almost temperature-independent transport. (e) Schematic of the ‘island-and-sea’ representation of charge distribution for different Fermi level positions as a function of gate voltage.
island-and-sea description in figure 3(e), has been reported in several different classes of low-dimensional systems, including dilute 2D electron or hole gases in high mobility semiconductor heterostructures [24, 25, 71, 72], silicon inversion layers [26], perovskite oxides [73], graphene nanoribbons [27, 74], or even MoS2 [21, 22] and WS2 [37] FET devices. However, the signatures of percolative transport in these systems are usually indirect and depend on the observation of metal—insulator transition [24, 25] or characteristic $I_d$ $-$ $V_d$ scaling [75, 76], which can also be limited to low temperatures and/or suffer from nonequilibrium effects. The noise—conductivity scaling constitutes a new probe to percolative transport in 2D TMDC materials where the divergence of noise associates the switching transition of the FET to the percolation threshold. In order to verify the generality of the observed $N_\sigma$ $-$ $\sigma$ scaling in other classes of TMDC FETs, we have carried out a noise experiment in similarly prepared backgated single layer MoS2 FETs on a SiO2 substrate (see table I for details). Three different devices with FE mobility up to $\mu \sim 20$ cm$^2$ V$^{-1}$ s$^{-1}$ (inset of figure 4(a)) were measured across the switching transition covering nearly five decades of change in conductivity (figure 4(a)). Figure 4(b) (inset) illustrates the typical gate voltage dependence of $N_\sigma$ in one of the devices (MoSSL_1) where we observe the noise magnitude to saturate at large doping ($V_g$ $\gtrsim$ $-40$ V). We have shown previously [47] that such a saturation arises from the remnant effects of the contacts and contributes additively to the total measured noise. Subtracting the contact noise $N_{\text{contact}}$ (dashed line in figure 4(b) inset), obtained by fitting the $V_G$ dependence of $N_\sigma$ at $V_g$ $\gtrsim$ $-35$ V, we recover the overall agreement between the channel noise ($N_\sigma$ $-$ $N_{\text{contact}}$) and the calculated MCW noise $N_{\text{MCW}}$ (equation (2)) over nearly five decades, suggesting that the noise in the annealed MoS2 FETs has a very similar microscopic origin as the WSe2 devices.

Figure 4(c) shows the scaling of $N_\sigma$ $-$ $N_{\text{contact}}$ with channel conductivity $\sigma$ for all three devices (shifted vertically with respect to each other for clarity). The scaling behavior is very similar in all cases where $\nu \approx 0.85 \pm 0.15$ at low $\sigma$ and crosses over to the continuum 2D percolation with random void ($\nu \approx 3$) above a characteristic conductivity of $\sigma_c \sim 5 \times 10^{-7}$ S/$.\square$. The MCW noise, estimated from experimentally measured $g_m$ (shown in figure 4(c) for MoSSL_2 with open circles), behaves in identical fashion over the entire range of $\sigma$ ensuring the consistency of the analysis. Interestingly, the magnitude of $\sigma_c$ is similar for WSe2 and MoS2 FETs, despite different materials and channel mobility. Importantly, MoS2 channels only show a divergence of noise with decreasing $V_G$, and no peak is observed even down to the smallest measured $\sigma (\approx 10^{-11}$ S/$\square$). This suggests that, unlike WSe2 FETs, conductivity below the percolation threshold in MoS2 FETs is too small to be measurable, possibly due to a predominantly long-range nature of the disorder. Hence, the observed $\nu (\approx 0.85)$ at $\sigma < \sigma_c$ in MoS2 is more likely to be due to continuum percolation in IRV (figure 3(e)) configuration, rather than the RR network. Nevertheless, the $N_\sigma$ $-$ $\sigma$ scaling in MoS2 FETs with universal exponents suggests that percolative transport at switching could be generic in TMDC FETs, although the nature of the percolation itself (discrete RR or continuum), is likely to depend on material details, channel mobility, disorder landscape, and other factors.
3. Conclusion

In conclusion, we have employed low-frequency 1/f noise in electrical conductivity to explore the nature of charge transport in FET devices with ultrathin TMDC channels, close to the switching transition at room temperature. The noise in both WSe2 and MoS2-based FETs arises from carrier number fluctuations, in agreement with previous experimental reports. Importantly, a unique scaling of the noise magnitude with channel conductivity in WSe2 FETs provides direct evidence of percolative electron flow at switching, which, in WSe2 FETs, crosses over from the RR network to continuum percolation with increasing carrier density. Similar behavior in MoS2 FETs suggests that percolative transport in inhomogeneous charge distribution at switching could be generic to other TMDC channels as well.

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