Transport in disordered monolayer MoS$_2$ nanoflakes—evidence for inhomogeneous charge transport

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Abstract
We study charge transport in a monolayer MoS$_2$ nanoflake over a wide range of carrier density, temperature and electric bias. We find that the transport is best described by a percolating picture in which the disorder breaks translational invariance, breaking the system up into a series of puddles, rather than previous pictures in which the disorder is treated as homogeneous and uniform. Our work provides insight to a unified picture of charge transport in monolayer MoS$_2$ nanoflakes and contributes to the development of next-generation MoS$_2$-based devices.

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

1. Introduction
Exploring a facile and controllable route to open a bandgap in graphene has been at the center of research into developing graphene-based nanoelectronics, which is considered to be a promising candidate in the coming post-silicon era with the continuing scaling down of device size to its physical limit. To date, a variety of methods such as chemical functionalization [1–6] and shape patterning [7–9] have been proposed to engineer the electrical properties of graphene. As an alternative option, layered transition metal dichalcogenide semiconductors such as molybdenum disulphide (MoS$_2$) have attracted renewed interest [10, 11]. In contrast to gapless graphene, two-dimensional (2D) monolayer MoS$_2$ has a direct bandgap of $\sim$1.6–1.8 eV, which makes MoS$_2$-based field-effect transistors (FETs) attractive due to their high on–off current ratio [12, 13]. In addition, since monolayer MoS$_2$ shares a similar hexagonal structure and 2D nature but has different electrical properties to those of graphene, several fascinating applications such as a high-gain phototransistor [14] and nonvolatile memory [15] were demonstrated based on MoS$_2$/graphene heterostructures. At present, a key challenge for MoS$_2$ to be applied in high-speed integrated circuits is the low carrier-mobility when deposited on substrates. Therefore much recent work has focused on improving the electrical performance of MoS$_2$ [16–18]. It has already been shown that encapsulation of MoS$_2$ in a high-$\kappa$ dielectric environment, where charged-impurity scattering is effectively suppressed, leads to a significant increase in the carrier mobility [18]. To fully utilize MoS$_2$ in applications, fundamental studies of charge transport in monolayer MoS$_2$ are essential.

In atomically thin 2D systems such as graphene, studies using local probes indicate that at low carrier densities or when disorder is strong, the system can break up into charge puddles [19, 20]. Similar observations of the formation of charge puddles have also been reported in conventional semiconductor-based 2D systems [21, 22]. For a wide variety of 2D systems, when the carrier density is decreased, the system becomes inhomogeneous, giving rise to charge puddles and a percolation transition [23–25]. The carrier density at which the inhomogeneity sets in depends on the magnitude of disorder. In graphene, at a low carrier density close to the
Dirac point, disorder originating from the randomly distributed trapped charges inside the substrate or near the graphene–substrate interface break up the 2D system into spatially inhomogeneous electron–hole puddles, even though they are not well isolated due to Klein tunnelling [26, 27]. If similar disorder were present in MoS₂, which has an intrinsic bandgap, it would be expected to break the system into inhomogeneous puddles of conducting electrons and insulating barriers.

Previous work on transport in MoS₂ has assumed the system to be uniform and has shown that variable-range hopping (VRH) conduction is responsible for the observed behavior [28, 29]. On the other hand, by suppressing the Coulomb impurity potential, a crossover from insulating behavior where the measured conductance $G$ decreases with decreasing temperature $T$ ($\frac{dG}{dT} > 0$) to metallic behavior ($\frac{dG}{dT} < 0$) is clearly visible with increasing the Fermi energy $E_F$ [18]. The underlying mechanism responsible for transport on the insulating side of this transition was explained in terms of thermally activated behavior rather than VRH. Very recently, Qiu et al [30] and Ghatak et al [31] reported interesting results that demonstrate that the structural inhomogeneity of MoS₂ itself also plays a role in the charge transport. Amongst these findings, a clear and unified picture of how disorder affects charge transport in MoS₂ is still lacking. In this paper, we perform detailed transport studies of an unencapsulated monolayer MoS₂ FET. We show that the experimental data can be well explained by the model of charge puddles. At high carrier densities and high temperatures, electron transport through charge puddles is the main mechanism. At very low temperatures or high disorder, transport via hopping occurs. Our work reconciles the two seemingly disparate views of inhomogeneous charge puddles and homogeneous hopping conduction in MoS₂ nanoflakes.

2. Experimental details

A monolayer MoS₂ nanoflake mechanically exfoliated from bulk MoS₂ crystal on the octadecyltrichlorosilane (OTS) functionalized SiO₂ (300 nm)/p⁺-Si substrate [32, 33] was identified by Raman spectroscopy with a 532 nm excitation laser. To avoid including extra disorder during the fabrication process, we adopted a resist-free method to deposit Au contacts [34]. DC transport measurements were performed in a close-cycle cryostat using two source measure units (Keithley 2400) to provide the back-gate and source-drain biases. Before measurements, the device was annealed at 140 °C under vacuum for 24 h to remove moisture absorbed on the MoS₂ surface. At temperatures below 190 K the current fails below the resolution of our instruments (using a Keithley 2400, the data is reliable for the measured current $I > 10^{-11}$ A and thus the conductance $G > 2 \times 10^{-10}$ S when $V_{SD} = 50$ mV is applied).

3. Results and discussion

We have performed transport measurements on a back-gated monolayer MoS₂ nanoflake with a room temperature mobility of $\sim 0.6$ cm²/Vs⁻¹. The basic characterization of the device, including the optical image and Raman spectrum, is presented in the supporting information. Figure 1 shows the conductance $G$ as a function of the back-gate voltage $V_{BG}$ at various temperatures $T$ from 300 K down to 90 K. The inset of figure 1 depicts the schematic diagram of the device. The conductance increases with increasing $V_{BG}$, showing typical n-type behavior. Figure 2(a) shows the corresponding conductance as a function of $1/T$ at different $V_{BG}$. We find that at high $V_{BG}$, the conductance increases with decreasing $T$, indicative of metallic behavior ($\frac{dG}{dT} < 0$), which is followed by insulating behavior ($\frac{dG}{dT} > 0$) below $T \sim 270$ K. In the insulating regime for $190 \leq T \leq 270$ K, the conductance can be well described by the thermally activated transport [18]

$$G(T) = G_b \exp \left( \frac{-E_b}{k_B T} \right),$$

where $E_b$ is the activation energy, $k_B$ is the Boltzmann constant, and $G_b$ is a prefactor. It is important to note that, in common with other studies, the data, which can be well fitted by the activation model, are also in good agreement with hopping since both of them predict an exponential $T$ dependence of $G$. Because of the limited temperature range of measurements, it is always difficult to distinguish between thermal activation and the different types of hopping. In general, hopping transport can be characterized as

$$G(T) = G_p \exp \left[ -\left( \frac{T_p}{T} \right)^\nu \right],$$

where $G_p$ is a prefactor, $T_p$ is a characteristic temperature, and...
In the following, we address the issue of distinguishing thermal activation from VRH in our device, which helps us understand the influence of disorder on the 2D electron system in monolayer MoS$_2$.

It has been suggested that the conductivity prefactor $\sigma_p$ should be much smaller than $e^2/h$ in phonon-assisted VRH or is on the order of $e^2/h$ when electron–electron interactions are significant [40]. For example, in reduced graphene oxide sheets, the prefactor $\sigma_{1/2}$ for ES-VRH behavior is found to be around $2e^2/h$ [41]. From the intercept of the fitting lines in figures S3(a) and (b), together with the known length-to-width ratio $\sim 1/6$ in figure S1(a) in the supporting information, we can obtain $\sigma_{1/3}$ and $\sigma_{1/2}$ for Mott and ES-VRH, respectively. The results at various $V_{BG}$ are presented in figure 2(b). We find that the obtained prefactor using the VRH model is much larger than $e^2/h$, which is inconsistent with the predictions of both phonon-assisted and interaction-assisted hopping described above. Instead, the prefactor determined from the fits to equation (1) is around $e^2/h$. In addition, in section 2 of the supporting information, we demonstrate that the weakening of $G(T)$ around $T=190$ K is not due to the crossover between Mott and ES VRH. Since both the nearest neighbor hopping (NNH) and activated transport can give rise to an exponential $T$ dependence of the conductivity as shown in figure 2(a), we need to check which is the dominant transport mechanism for $190$ K $\leq T \leq 270$ K. It is well established that for disordered systems, conduction can be separated into various temperature regimes, based on Mott’s concept of a mobility edge [35, 36].

(i) At very high temperatures ($T>280$ K in our experiments), a large number of carriers around $E_F$ are excited to the delocalized states above the mobility edge $E_{m,n}$, and we will observe metallic behavior due to electron–phonon interactions, which means that the conductance $G$ increases with decreasing $T$.

(ii) Upon reducing the temperature, the number of carriers that can be thermally activated to delocalized states decreases, giving a conduction that follows an Arrhenius form $G(T)=G_0 \exp(-E_0/kT)$. In the percolation model, the activation energy $E_0$ is equivalent to the potential barrier $E_b$ ($=E_{m,n}-E_F$) that separates the charge puddles.

(iii) Upon further decreasing the temperature, these thermal excitation processes to the mobility edge are no longer possible, and conduction occurs by thermally assisted hopping between localized states. At first, conduction occurs by hopping between adjacent localized states, the so-called NNH. Nearest neighbor hopping also gives $G(T)=G_0 \exp(-E_0/kT)$.

In our experiments, the metallic behavior (mechanism (i)) is observed at high temperatures ($T>280$ K). Therefore, the thermally activated behaviour we observe in the interval $190$ K $\leq T \leq 270$ K cannot be due to NNH (mechanism (iii)), since activation of carriers from localized to delocalized states must come first (mechanism (ii)). Based on these experimental results, we can infer that activated transport, rather than VRH and NNH, is the reasonable mechanism in our gated MoS$_2$ device for $190$ K $\leq T \leq 270$ K. More interestingly,
thermal activation with a prefactor on the order of $e^2/h$ is usually observed in an inhomogeneous system considering transport through a saddle point junction between charge puddles [42, 43]. This percolating picture has been demonstrated to be crucial in a variety of transition phenomena such as the metal–insulator transition [23, 24], superconductor–insulator transition [44, 45] and quantum Hall plateau–plateau transition [46, 47].

The inset of figure 2(a) presents the activation energy $E_b$ as a function of $V_{BG}$, which is obtained from the slopes shown in figure 2(a). If the random potential is independent of carrier density, we would expect the effective barrier height to go as $<E_b> = <E_b^0 - E_F>$, where $E_b^0$ is the energy of percolation threshold. In two dimensions, $E_b^0$ is given by $n_sN(E_b^0)$, where the carrier density $n_s$ is controlled by the back gate. Hence we expect $E_b$ to vary linearly with $V_{BG}$, as seen in the data. In monolayer MoS$_2$, the ideal value of the density of states is $\frac{2m^*}{\pi^2} = 3.8 \times 10^{18}$ eV$^{-1}$ m$^{-2}$. Using the parallel-plate capacitor model with $n = C_{ox} \frac{(V_{BG} - V_{BG}^0)}{\varepsilon}$ and assuming that $C_{ox} = 1.15 \times 10^{-4}$ F m$^{-2}$ for the 300 nm-thick SiO$_2$ used, we can then estimate the ideal value of $\frac{dE_b}{dV_{BG}} = 0.19$ meV V$^{-1}$, which is smaller than the measured slope of 2.77 meV V$^{-1}$ in the inset of figure 2(a). Here $m^*$, $\varepsilon$, $n$, $C_{ox}$ and $V_{BG}^0$ represent the effective mass ( 0.45 m$_e$) for MoS$_2$ [18], reduced Plank constant, carrier density, capacitance per unit area and threshold voltage, respectively. The discrepancy between theory and experiment is ascribed to $E_b^0$ itself changing with $V_{BG}$—that is, the disorder potential is affected by the carrier density. On the other hand, in disordered MoS$_2$, charged disorder can reduce the carrier density, both by raising the bottom of the conduction band and by introducing lateral potential confinement, which creates charge puddles. Both of these can cause a much lower value of $N(E_b)$ and thereby a larger value of $\frac{dE_b}{dV_{BG}}$ with respect to the ideal one. In section 3 of the supporting information, we further characterize the MoS$_2$ device by illumination and exposure to air.

We note that below 190 K, the measured conductance is higher than that given by equation (1), suggesting that there is an additional conduction mechanism at low $T$. After identifying the thermal activation as the dominant transport mechanism for 190 K $\leq T \lesssim 270$ K, we also need to clarify the observed deviation from equation (1) for $T < 190$ K. Since we already know $G_0$ and $E_b$ of equation (1) from the fits for 190 K $\leq T \lesssim 270$ K, the net contribution of the second transport mechanism below $T \approx 190$ K can be determined by subtracting $G_0 \exp\left(\frac{-E_b}{k_B T}\right)$ from the experimentally measured $G(T)$. In the supporting information, this second transport mechanism is strongly temperature-dependent. However it is hard to identify the exact nature of this second transport mechanism. Figures S6(a)–(c) show that $G - G_0 \exp\left(\frac{-E_b}{k_B T}\right)$ can be well described by not only $G_0 \exp\left(\frac{-E_b}{k_B T}\right)$ due to thermally assisted tunnelling but also the VRH model according to equation (2). Figure S6(d) in the supporting information presents the obtained prefactors using the three different models, all of which are now reasonable. For clarity, we show that the red fitting curves in figure 2(a) demonstrate the good agreement of the conductance data with $G_0 \exp\left(\frac{-E_b}{k_B T}\right) + G_M \exp\left(\frac{-E_b}{k_B T}\right)$ below 190 K using the obtained parameters. Note that both ES and Mott VRH models can also provide satisfactory explanation for our data at $T < 190$ K, as shown in the supporting information, figures S6(e) and (f), respectively. Therefore we cannot distinguish between different types of hopping in this regime. Nevertheless, our analysis clearly shows that at high $T$ transport is by thermal activation over large barriers $E_b$, and at low $T$ tunnelling via impurities sets in.

To provide further evidence for the existence of charge puddles, we study the evolution of current–voltage characteristics $I(V_{SD})$ with temperature and back-gate bias in figures 3 and 4. The raw data at three representative temperatures $T = 300$ K, $200$ K and $100$ K, are presented in the supporting information, figures S7(a)–(c). The $I(V_{SD})$ becomes nonlinear with decreasing $T$ at $V_{BG} = 50$ V. Since the measured $I$ does not show an exponential increase with $V_{SD}$, as seen from the semi-log plot of $I$ vs $V_{SD}$ in the supporting information, figure S8, we can rule out the possibility that the
The nonlinearity is due to the non-ideal ohmic contacts behaving as a Schottky barrier [31]. Figure 3(a) then shows $I(V_{BG})$ at various $V_{BG}$ ranging from 50 V to 10 V for $T=200$ K. From top to bottom, $V_{BG} = 50$ V, 45 V, 40 V, 35 V, 30 V, 25 V, 20 V, 15 V and 10 V. (b) A log–log plot of $I$ versus $V_{SD}$ at various $V_{BG}$, ranging from 50 V to 10 V for $T=200$ K. The solid line shows $\zeta = 1.3$. (b) The corresponding $V_t$ as a function of $V_{BG}$. For $V_{BG} \geq 35$ V, the linear fit to the data is shown as the red line.

Experimentally, scaling behavior following equation (3) with a wide spread in $\zeta$ have been reported in a variety of inhomogeneous 2D systems such as metal dot arrays [50], metal nanocrystal arrays [51], graphene quantum dot arrays [52], and an electrostatically defined quantum dot lattice in a GaAs-based 2D electron gas [53]. To apply the MW model in analyzing the data, we need to first identify $V_t$. However, for $T > 60$ K, a clear threshold is absent in figure 3(a). We therefore choose $V_t$ such that the $I(V_{SD})$ traces of two successive temperatures can collapse on top of each other at high $V_{SD}$ by using equation (3). Figure 3(b) then shows a log–log plot of the current $I$ as a function of the scaling parameter $\frac{V_{SD}}{V_t} - 1$ at various $T$. We find that for $120$ K $\leq T \leq 200$ K, at high $V_{SD}$ the $I(V_{SD})$ characteristics show power-law scaling-like behavior with $\zeta = 1.3$ [53]—characteristics of a percolation transition and further evidence for existence of charge puddles in our system.

We note that $\zeta$ deviates from 1.3 when $T < 120$ K and increases with decreasing $T$. Figure 3(c) summarizes the determined $V_t$ as a function of $T$. Interestingly, it shows that $V_t$ increases dramatically when $T < 120$ K and approximately linearly with $T$ for $T > 120$ K. It has already been demonstrated both experimentally and theoretically that increasing background charge disorder can significantly enhance $V_t$ and invalidate the scaling law of equation (3) [51–55]. Figures 4(a) and (b) then show $I$ as a function of $V_{SD}$ and of the scaling parameter $\frac{V_{SD}}{V_t} - 1$ at various $V_{BG}$ for $T=200$ K on a log–log scale. Similarly, $V_t$ is chosen such that the traces of two successive back-gate voltages with a step of 5 V can collapse on top of each other at high $V_{SD}$. The obtained $V_t$, as a function of $V_{BG}$ is presented in figure 4(c). We can also observe that $V_t$ increases rapidly when $V_{BG} < 35$ V and approximately linearly with $V_{BG}$ for $V_{BG} \geq 35$ V. Therefore we know that the effective disorder changes with $V_{BG}$ as inferred from the much larger slope of $\frac{dG}{dV_t}$ compared with the ideal value.

At high $V_{BG}$, it has been reported that the metallic behavior can sustain at much lower $T$ in high-mobility MoS$_2$ devices [18]. However, in an unencapsulated MoS$_2$ nanoflake, disorder arising from external charged impurities or structural inhomogeneity may cause spatial fluctuations in the conduction band edge $E_c$, breaking up the ideally uniform 2D electron system into a distribution of charge puddles. Our results suggest that we can develop a model of charge puddles in the monolayer MoS$_2$. The picture in figure 5 captures the essence of this model. The puddles locate at the regions of higher carrier density and are immersed into the background of trapped states. We note that the conduction paths that give lower resistance compared to the other ones in parallel will dominate the resulting transport behavior. As depicted in figure 5, at high temperatures and high densities, transport through puddles is relatively easy and thus predominantly governs $G(T)$. When the coupling of puddles is strong, there exist accessible extended states above the Mott mobility edge. Therefore the metallic properties of MoS$_2$ can result in the increase of $G$ with decreasing $T$, as found in figure 2(a). With decreasing $T$, thermal activation of carriers between puddles...
are the puddle area described by equation (1). As demonstrated in Nanotechnology 25 (2014) 375201 S-T Lo et al

Figure 5. Schematic diagram illustrating different paths of carrier conduction. The shaded regions represent the charge puddles and the circles are for the trapped states. The black and red arrows correspond to the trajectories of transport through puddles and those of hopping process along trapped states, respectively.

is gradually suppressed and the system shows insulating behavior described by equation (1). As demonstrated in figure 2(a), for $T<190$ K, thermally assisted tunnelling or hopping conduction becomes more important as the temperature is lowered. We observe that $I(V_{SD})$ follows the scaling law of equation (3) with $\zeta=1.3$ for $120$ K $\leq T \leq 200$ K, suggesting the importance of transport through puddles. At sufficiently low $T$ (<120 K) when the carriers are difficult to conduct directly through puddles, thermally assisted tunnelling between puddles mediated by the surrounding trapped states or hopping along the trapped states is preferred instead, which is depicted in figure 5. Since the carrier conduction is strongly hindered due to the existence of trapped sites, it is expected that the measured $I$ will decrease more rapidly with decreasing $V_{SD}$ than that predicted by equation (3) when hopping conduction is important. Hence, these trapped states cause an increase in $\zeta$ and eventually invalidate equation (3) with decreasing $T$, as shown in figure 3(b).

According to the MW model, the characteristic exponent $\zeta$ of the power-law scaling is determined by the effective dimensionality of the conducting channels. It is correct that the MW model suggests that $\zeta=1.6$ to 2 for 2D. However in 1D (i.e., only one preferred path or a small number of paths carry a majority of the current), the MW model gives $\zeta=1$. In our experiments, $\zeta=1.3$ was found. For example, in the presence of two different kinds of disorder (which create puddles and trapped states, respectively) as depicted in figure 5, it can be expected that a 1D channel through puddles dominates the transport at low $T$, since multiple hops between the localized states are much less efficient than hopping between 2D puddles. The key point is that if the system becomes inhomogeneous, the disorder breaks the translational symmetry—the system is no longer purely two-dimensional, and is between the 2D ($1.6<\zeta<2$) and 1D ($\zeta=1$) limits. The observed scaling behavior with $\zeta=1.3$ in our measurements thereby indicates the inhomogeneity of the measured MoS$_2$ nanoflake. We note that the mobility of graphene prepared on an OTS functionalized SiO$_2$ substrate is only about two times higher than that of graphene prepared on a SiO$_2$ substrate [32]. Therefore, although OTS functionalized SiO$_2$ can substantially reduce the disorder effect from the substrate, the substrate still affects the transport properties of 2D materials such as graphene and MoS$_2$. It is worth mentioning that the seminal work of Qiu et al [30], which combine transport measurements, transmission electron microscopy, density functional theory and tight-binding calculations, has demonstrated the importance of sulphur vacancies on the localization behavior in MoS$_2$. Accompanied by the presence of sulphur vacancies the unsaturated electrons in the surrounding Mo atoms, which act as donors to make MoS$_2$ behave as an n-type semiconductor. Therefore we believe that both the substrate and intrinsic defects such as sulphur vacancies contribute to the formation of puddles in our MoS$_2$ devices.

As shown in the supporting information, figure S9, no clear Coulomb oscillations due to charging are observed at $T>40$ K. Thus we can estimate the charging energy of the puddle $e^2/C$ to be less than the thermal energy $k_BT$ at 40 K, where $k_B$ is the Boltzmann constant. Using the simple capacitor calculation $C=\frac{\varepsilon\varepsilon_0 A}{d}$, where $A$ and $d$ are the puddle area and the thickness of the SiO$_2$ layer (=300 nm), respectively, this yields a length scale of $\approx 600$ nm. However, we wish to point out that within this approach, we only calculate the gate capacitance, and the total capacitance has been under-estimated. Therefore this length scale represents the upper bound for the puddle size.

Either decreasing $T$ or $V_{BG}$ will reduce the conduction current of MoS$_2$. However, as shown in figure 4(b), the scaling behavior with the exponent 1.3 is shown to remain valid even down to $V_{BG}=10$ V with $I<1$ nA, which suggests that puddle physics may still govern the carrier transport at low $V_{BG}$. This is due to the fact that decreasing $T$ from 200 K to 20 K can change the ratio of $\frac{E_0}{k_BT}$ in equation (1) by a factor of 10. However, $\frac{E_0}{k_BT}$ would not be highly dependent on $V_{BG}$ since the variation of $E_0$ with $V_g$ is not huge (about two times when $V_{BG}$ is reduced from 50 V to 10 V) as in the inset of figure 2(c), which can explain the survival of the power-law scaling of equation (3) with $\zeta=1.3$ at low $V_{BG}$ in figure 4(b). As another evidence for the inhomogeneity of MoS$_2$, the current exhibits weak peak structures in the back-gate voltage when $T<100$ K in the supporting information, figure S9 [28, 46]. We therefore suggest that transport through puddles is dominant for $T>120$ K and is mediated by the surrounding trapped states below $T=120$ K. Instead of all electronic states, which show strongly localized behavior under the assumption of homogenous disorder, we demonstrate that charge puddles...
(inhomogeneity) can be present in a disordered monolayer MoS2 flake by studying the evolution of the conduction current when varying the measurement temperature, carrier density and source-drain bias. The combination effects of disorder from substrates and from structural inhomogeneity are expected to be the underlying reason. Our results may pave the way for obtaining a unified picture of carrier transport in monolayer MoS2 flakes, which is important for advanced applications of MoS2 in transistors, biosensors, photodetectors etc.

4. Conclusion

In conclusion, we have demonstrated that charge puddles can be present in a disordered monolayer MoS2 flake. Varying the carrier density and temperature effectively modifies the coupling between different puddles and thus changes the dominant transport mechanism correspondingly. At high carrier densities and temperatures, metallic behavior is observed since the correlation between puddles is strong. With decreasing temperature, thermal activation across the potential barrier that separates the puddles governs the transport. With further decreasing temperature, which decreases the correlation of puddles, deviation from a simple activation scheme is found. We show that it is associated to thermally assisted tunnelling along trapped states, which provides an extra contribution to the transport at low temperatures. In the same temperature range, we find that the current–voltage characteristics tend to follow power-law scaling behavior with the exponent 1.3, which is a characteristic signature of percolation and further confirms the existence of charge puddles. These results contribute not only to our basic understanding of charge transport in monolayer MoS2 but also to the development of next-generation nanoelectronics based on atomically thin two-dimensional materials.

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