Restricted Channel Migration in 2D Multilayer ReS₂

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Abstract: When the thickness-dependent carrier mobility is coupled with Thomas-Fermi screening and interlayer resistance effects in two-dimensional (2D) multilayer materials, a conducting channel migrates from the bottom surface to the top surface under electrostatic bias conditions. However, numerous factors including i) an insufficient carrier density, ii) atomically thin material thickness, and iii) numerous oxide trap/defects considerably limit our deep understanding of the carrier transport mechanism in 2D multilayer materials. Herein, we report the restricted conducting channel migration in a 2D multilayer ReS_2 after a constant voltage stress of the gate dielectrics is applied. At a given gate bias condition, a gradual increase in the drain bias enables a sensitive change in the interlayer resistance of ReS_2 , leading to a modification of the shape of the transconductance curves, and consequently demonstrates the conducting channel migration along the thickness of the ReS_2 before the stress. Meanwhile, this distinct conduction feature disappears after stress, indicating the formation of additional oxide trap sites inside the gate dielectrics that degrade the carrier mobility and eventually restrict the channel migration. Our theoretical and experimental study based on the resistor network model and Thomas–Fermi charge screening theory provides further insight into the origins of channel migration and restriction in 2D multilayer devices.

INTRODUCTION

Among numerous two-dimensional (2D) van der Waals (vdW) layered materials, a distorted octahedral (1T') rhenium disulfide (ReS₂) multilayer provides unique properties such as anisotropic in-plane carrier transport,¹⁻⁴ a thickness-independent direct bandgap at approximately 1.5 eV,^{5,6} and weak interlayer coupling.^{5,7} These intrinsic properties of ReS₂ allow various applications such as a field-effect transistor,^{1,3,8,9} tunneling diode,¹⁰⁻¹² logic device,^{4,13,14} and phototransistor with excellent responsivity, absorption efficiency, and detectivity to be demonstrated.¹⁵⁻¹⁷ In particular, the strongly decoupled interlayer interaction in the multilayer ReS₂ leads to a relatively larger interlayer resistivity ($\sim 10^5 \Omega \cdot \mu\text{m}$)¹⁸ than that of other 2D transition metal dichalcogenide materials such as MoS₂ ($\sim 10^3 \Omega \cdot \mu\text{m}$)^{19,20} and graphite ($\sim 10^2 \Omega \cdot \mu\text{m}$),²⁰ rendering this multilayer ReS₂ an ideal platform for studying the carrier transport mechanism among other 2D vdW multilayer materials. When this interlayer energy barrier is coupled with the thickness-dependent carrier mobility and Thomas–Fermi screening effects in 2D multilayer materials, it has been theoretically and experimentally demonstrated that a conducting channel migrates from the bottom surface to the top surface under electrostatic bias conditions,^{3,19,20} which is in clear contrast to their Si bulk counterparts where its inversion channel centroid exhibits nearby gate dielectrics.^{3,21,22}

For example, Das et al. systematically reported a non-monotonic thickness-dependent carrier mobility with respect to different metal electrodes ascribing to the Thomas–Fermi charge screening and interlayer coupling in MoS₂ multilayers.^{19,20} In addition, Shim and Moon et al. investigated systematically the thickness-dependent optoelectronic properties of ReS₂ thin film transistors,^{14,16} and Lee and Kim et al. probed the effects of interlayer tunneling barrier effects on the current fluctuation in a multilayer ReS₂ transistor with respect to the top and bottom surfaces.^{3,21} Furthermore, Goyal et al. demonstrated a feasible memory

application using few-layer ReS_2 transistors upon the observance of two plateaus in its transconductance curves.²³ Nevertheless, this genetic carrier transport mechanism of a 2D multilayer platform has not been extensively explored because of i) an insufficient electrostatic vertical electric field or minimum accumulated carrier density necessary to observe the conducting channel redistribution, ii) an atomically thin material thickness limiting the spatial channel migration, and iii) numerous oxide trap/defect sites degrading carrier mobility. These experimental constraints considerably prevent our full understanding of the carrier transport mechanism in 2D multilayer materials, consequently implying the importance of the thickness of such materials and the degree of the interlayer energy barrier, which relies strongly on the electrostatic drain (V_D) and gate (V_{BG}) bias conditions to achieve a clear insight into the distinct carrier transport mechanism in multiple 2D layers.

Herein, we report the restricted drain bias-dependent conducting channel migration in a 2D multilayer ReS_2 device by presenting i) the presence of two plateaus and their shape modification in the transconductance (g_m), and ii) a variation of the turn-on voltage (V_T) shift with respect to the top and bottom channels as a function of the drain voltage before and after electrical stress at $V_{BG} = 60$ V for 40,000 s. Within a small V_D regime of 20 to 100 mV, the channel centroid migration is clearly observed before the V_{BG} stress, whereas the channel centroid is mostly confined within the multilayer ReS_2 after the V_{BG} stress, masking the formation of the conducting channel near the degraded gate dielectrics. Meanwhile, as V_D increases, the separated top- and bottom-channel combines together regardless of the stress. The degradation in carrier mobility after the electrical stress further supports the presence of additional oxide trap sites, which hampers the channel formation at the bottom layers, consequently leading to a restricted channel migration. Our numerical resistor network calculation, which considers the Thomas–Fermi screening effect and interlayer resistance,

further rationalizes this anomalous carrier transport feature in a 2D multilayer ReS₂.

RESULTS AND DISCUSSION

To achieve a clear insight regarding the physical origin of channel migration and restriction in 2D multilayer devices, we first consider the resistor network model and Thomas–Fermi charge screening theory, as illustrated conceptually in Figure 1a, for a pristine ReS₂ device.

The thickness-dependent effective carrier mobility (μ_i) corresponding to a certain layer thickness (i^{th} layer of 2D vdW multilayer materials) has been described by

$\mu_i = \mu_1 + (\mu_\infty - \mu_1) \left(1 - \exp\left(-\frac{(i-1)t_{\text{Int}}}{\lambda_{\text{TF}}}\right) \right)$,^{19,20} where μ_1 ($= 1 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$),¹ μ_∞ ($= 200 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$),^{13,24} and t_{Int} ($= 0.65 \text{ nm}$) are the monolayer mobility of ReS₂, bulk carrier mobility of ReS₂, and interlayer distance, respectively. Such an anomalous carrier mobility enhancement along the thickness (up to 10 nm) at the given V_{BG} and V_{D} conditions for the i^{th} layer of a 2D multilayer system can mainly be ascribed to the presence of fixed oxide charges inside the dielectrics and charged Coulomb impurities on the bottom and/or top surfaces of the 2D materials, in addition to an interlayer resistance and the effects of the Thomas-Fermi screening.^{13,16,25,26} The thickness-dependent carrier mobility of multilayer ReS₂ is presented elsewhere, including our previous report.^{16,27} The Thomas–Fermi charge screening length

$(\lambda_{\text{TF}} = \sqrt{\left(\frac{\epsilon_{\text{ReS}_2}}{\epsilon_{\text{SiO}_2}}\right) t_{\text{ReS}_2} t_{\text{SiO}_2}}$, where $\epsilon_{\text{ReS}_2}/\epsilon_{\text{SiO}_2}$ ($= 7/3.9$)²⁸ and $t_{\text{ReS}_2}/t_{\text{SiO}_2}$ ($= 11 \text{ nm}/90 \text{ nm}$)

denote the dielectric constant and thickness of ReS₂/SiO₂, respectively.) used in our multilayer ReS₂ is $\approx 42 \text{ nm}$, which is much thicker than the t_{ReS_2} in this study, implying the proper thickness range of the ReS₂ in the vertical direction. The much smaller value of λ_{TF} than L_{ReS_2} allows a negligible contribution of the fringing field effect on the oxide planar capacitance (C_{OX}).^{19,20} In addition, provided that we obtain the charge density of the i^{th} layer

(Q_i) by taking into account λ_{TF} and the screened Coulomb potential of the i^{th} layer according to the Thomas–Fermi screening theory, the conductivity ($\sigma_i = Q_i \times \mu_i$) and conductance ($G_i = \sigma_i \times (W/L)$, where W and L are the channel width and length, respectively) can be determined for each layer, enabling the visualization of which layer is the most conducting layer inside the multilayer ReS_2 .^{3,19} Based on the resistor network model, the drain current contribution of the i^{th} layer (I_D^i) to the total drain current ($= \sum_i I_D^i$) can be confirmed under the boundary condition of the interlayer resistivity of ReS_2 ($R_{\text{Int}} = 10^5 \Omega \cdot \mu\text{m}$). This R_{Int} range of ReS_2 was further supported by the voltage-dependent current obtained from a 12-nm thick ReS_2 *via* conductive-AFM (c-AFM) using a Pt-coated tip ($= 25 \text{ nm}$) (see Figure S1 in the Supporting Information (SI)). As V_{BG} increases, the channel that exhibits the highest conductivity in the layers migrates from the bottom surface to the top surface of the ReS_2 in a conventional back-gate configuration mainly owing to the interplay between R_{Int} and λ_{TF} , mirroring the V_{BG} -dependent spatial channel modification. This is a distinct feature in comparison with monolayer and conventional 3D bulk semiconductor systems. A more detailed explanation of this theoretical approach is described elsewhere.^{3,19,21}

The numerically calculated R_{Int} -dependent current distribution profile along the thickness of ReS_2 as a function of V_{BG} after the maximum current normalization for each layer is displayed in Figures 1b-d display, where I_{D_max} is the maximum I_D among I_D^i . Here, we take the variable R_{Int} into account our calculation ranging from 10^2 to $10^4 \Omega \cdot \mu\text{m}$ for a deeper understanding of channel migration in 2D multilayer. When R_{Int} is $10^2 \Omega \cdot \mu\text{m}$, the significant channel migration is not observed clearly, although the relative volume of top-channel expands slightly (see Figure 1b). However, when R_{Int} is larger than $10^3 \Omega \cdot \mu\text{m}$ (see Figures 1c-d), the conducting channel centroid tends to move upward to exclude large contribution of R_{Int} in its total resistance of ReS_2 with the increasing V_{BG} , implying clearly that the enhanced

contribution of top-channel to the total current comparing to that of bottom-channel. In addition, this fact further suggests that this distinct channel migration can be tuned by V_D because of R_{Int} (or the interlayer tunneling barrier height) reliance on V_D in addition to V_{BG} . These results clearly demonstrate the importance role of R_{Int} in the transport mechanism of 2D vdW multilayers.

Next, we investigate the restricted channel migration in 2D vdW multilayers by assuming that the carrier mobility is degraded by the electrical V_{BG} stress, as illustrated in Figure 1e. The additional oxide trap sites created inside the dielectrics considerably reduces μ_i and suppresses Q_i for the bottom layers in particular,^{25,29–31} hampering the bottom channel formation inside the multilayer ReS_2 , and consequently leading to a restricted spatial channel migration. Figures 1f–h further support this restriction, which is obtained from our numerical calculation by taking the degradation of the carrier mobility into account as a function of R_{Int} . Herein, we simply assume $\mu_1 - \mu_5 (= 0.5 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1})$ and $\mu_{\infty} (= 200 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1})$ to reflect the effects of the oxide trap. It has been reported that the electrical V_{BG} stress degrades the oxide quality by creating undesired oxide trap/defect inside the dielectrics.^{31–34} This oxide degradation is often linked to a gate dielectric break down, a severe malfunction of the analog/digital circuit, and the life time of the memory. Understanding the effects of the oxide quality degradation on this distinct 2D carrier transport is essential for employing various 2D materials as next-generation logic devices and optoelectronics.

Figure 1. Conducting channel migration and restriction in 2D multilayer ReS₂. (a) Conceptual illustration of conducting channel migration as a function of V_{BG} at a given thickness-dependent carrier mobility μ . Numerical simulation results for current distribution along the c -axis of ReS₂ as a function of R_{Int} ; (b) $R_{\text{Int}} = 10^2 \Omega \cdot \mu\text{m}$, (c) $R_{\text{Int}} = 10^3 \Omega \cdot \mu\text{m}$, and (d) $R_{\text{Int}} = 10^4 \Omega \cdot \mu\text{m}$. (e-h) Corresponding panels after electrical V_{BG} stress. (e) Illustration of restricted channel migration after V_{BG} stress. The oxide trap sites created degrade the carrier mobility, particularly at the bottom layers, which hampers the formation of the bottom channel. R_{Int} -dependent current distribution after the V_{BG} stress in terms of (f) $R_{\text{Int}} = 10^2 \Omega \cdot \mu\text{m}$, (g) $R_{\text{Int}} = 10^3 \Omega \cdot \mu\text{m}$, and (h) $R_{\text{Int}} = 10^4 \Omega \cdot \mu\text{m}$.

To study this anomalous feature of multilayer ReS₂, we fabricated an 11-nm thick 1T' multilayer ReS₂ transistor onto a 90-nm thick SiO₂/p⁺-Si substrate and investigated the variation of the carrier transport mechanism before and after applying electrical stress at $V_{\text{BG}} = 60$ V for 40,000 s with a zero-drain and source bias, as illustrated in Figures 2a and b, respectively. The fabricated device was thermally annealed for 3 h at 473 K under a high vacuum condition ($\approx 10^{-6}$ Torr). A detailed description of the device fabrication is presented in the Experimental Section. The various geometrical parameters of the pristine multilayer ReS₂, such as L ($\approx 1 \mu\text{m}$), W ($\approx 0.614 \mu\text{m}$), and t_{ReS_2} (≈ 11 nm) were confirmed using an atomic

force microscope (AFM) (see Figure 2c). The negligible thickness difference at the whole channel confirmed by AFM clearly demonstrates a uniform thickness of our ReS₂. The optical Raman spectrum obtained from 11-nm thick ReS₂ under ambient conditions using a laser excitation wavelength of 532 nm (λ_{EX}) with 5 mW of power (P) is shown in Figure 2d. The dominant E_g ($\approx 150 \sim 160 \text{ cm}^{-1}$), A_{1g} -like ($\approx 215 \text{ cm}^{-1}$), and E_g -like ($\approx 312 \text{ cm}^{-1}$) are clearly observed, which is consistent with previous reports.^{5,16}

Figure 2. Device structure and optical Raman property of 2D multilayer ReS₂. Cross-sectional view of a multilayer ReS₂ transistor in (a) pristine state and (b) after V_{BG} stress. (c) AFM topography image of multilayer ReS₂ fabricated on SiO₂. The thickness profiles along the numerous lines are displayed in the right inset. (d) Raman spectrum of 11-nm-thick ReS₂ flake on SiO₂ substrate measured at $\lambda_{\text{EX}} = 532 \text{ nm}$ with $P = 5 \text{ mW}$.

The two-probe measured V_{BG} -dependent conductance ($G = I_{\text{D}}/V_{\text{D}}$) curves of the pristine ReS₂ transistor clearly represent a typical n -type behavior, in which the populated electrons are visible with increasing V_{BG} (see Figures 3a–c) regardless of V_{D} . To further reveal the

physical implications of V_D -dependent G curves, the corresponding g_m ($=\partial I_D/\partial V_{BG}$) normalized by V_D ($=g_m/V_D$ or $\partial G/\partial V_{BG}$) curves are directly compared in the same panel. In principle, the G (or g_m/V_D) curves obtained should be identical regardless of V_D when there is a negligible metal-to-ReS₂ Schottky barrier, particularly for very small V_D regimes.²¹ This feature is observed in our multilayer ReS₂ device. However, as V_D increases from 10 to 100 mV (see Figure 3a), two plateaus are clearly exhibited in the g_m/V_D curve at near $V_D = 100$ mV, implying the emergence of channel migration, which was mainly triggered by the increasing V_D , as previously described (see Figures 1a–d). Indeed, the double enhancement of g_m has been interpreted as the coexistence of a different conduction mechanism, e.g., MoS₂/Gr heterointerface transistors^{35,36}, double-gate silicon-on-insulator transistors³⁷, and Si junction-less transistors^{38,39}. Moreover, the two peaks observed for the g_m/V_D curve are gradually merged (see Figure 3b), which is further broadened and extended with an increase in V_D (see Figure 3c). This V_D dependency in the observed g_m/V_D indicates the suppression of R_{int} , resulting in a channel migration and carrier mobility enhancement, particularly at high V_D regimes. This observation is in clear contrast to the conventional short-channel effects in Si transistors driven by the drain-induced-barrier-lowering, which degrades the carrier mobility in high V_D regimes.⁴⁰

This anomalous signature indicating a channel migration is significantly suppressed after the electrical V_{BG} stress, particularly in small V_D regimes (see Figure 3d). The V_{BG} -dependent G and g_m/V_D curves are almost identical to each other regardless of V_D , mirroring the spatially limited channel migration in the observed small V_D . The oxide traps created in the SiO₂ under the V_{BG} stress degrade the carrier mobility and suppress the available free electrons inside ReS₂, which makes the bottom-channel formation difficult, consequently leading to a restricted channel migration, as we previously demonstrated (see Figures 1e–h). Nevertheless,

in high V_D regimes, the observed g_m/V_D after the V_{BG} stress demonstrates features similar to those of pristine ReS₂ (see Figures 3e and f), implying the stronger contribution of damaged oxide traps to the bottom channel formation rather than the top channel formation inside the ReS₂. In addition, the narrower distance of V_{BG} between the first and second maximum g_m/V_D after the V_{BG} stress also demonstrates the limited spatial channel migration.

Figure 3. Electrical properties of 2D multilayer ReS₂. (a–c) V_D -dependent G ($= I_D/V_D$, the solid lines with the left y-axis) and g_m normalized by V_D curves ($= g_m/V_D$, the dotted lines with the right y-axis) under pristine condition at (a) $10 \text{ mV} \leq V_D \leq 100 \text{ mV}$, (b) $100 \text{ mV} \leq V_D \leq 900 \text{ mV}$, and (c) $2 \text{ V} \leq V_D \leq 5 \text{ V}$, respectively. (d–e) The corresponding results after the V_{BG} stress at (d) $10 \text{ mV} \leq V_D \leq 100 \text{ mV}$, (e) $100 \text{ mV} \leq V_D \leq 900 \text{ mV}$, and (f) $2 \text{ V} \leq V_D \leq 5 \text{ V}$, respectively.

To qualitatively discuss the channel migration and restriction, the turn-on voltage (V_T) for the bottom and top channels of the multilayer ReS₂ was determined using the second-derivative of the current method ($dg_m = \partial g_m / \partial V_{BG}$) before and after the V_{BG} stress (see Figures 4a and b).⁴¹ In these figures, when V_D is less than 100 mV, owing to the existence of two clear

humps of g_m , the first and second maximum dg_m peaks of the pristine ReS₂ (after the V_{BG} stress) clearly appear at $V_{BG} \approx -18.5$ V ($V_{BG} \approx -14.5$ V) and 2.5 V $\leq V_{BG} \leq 12$ V (4.5 V $\leq V_{BG} \leq 9.5$ V), respectively. However, as V_D increases, both peaks gradually merge together and eventually exhibit a single dg_m peak at V_D higher than 100 mV (see Figure 4c), manifesting a broadening channel inside the multilayer ReS₂ by combining the top and bottom channels. The upshifted V_T after the V_{BG} stress particularly for the bottom channel mirrors the additionally created trap density to be filled, i.e., $C_{OX}/q \times (5 \text{ V}) \approx 1.2 \times 10^{12} \text{ cm}^{-2}$, where q denotes the electronic unit charge and consequently limits the total channel migration distance along the c -axis of the ReS₂. The irreversible conductance and enhancement of gate leakage current after the electrical stress and recovery further support this observation as displayed in Figure S2 in the Supporting Information. We further note that taking into account of our device configuration (p^+ -Si/SiO₂/ n^+ -ReS₂/Au), the established electric field should be mainly focused on SiO₂ (i.e., the most resistive (or capacitive) element), implying a negligible Joule heating effect of current on our ReS₂.

Moreover, the abrupt change in the difference in V_T observed between the top and bottom channels (ΔV_T) after the V_{BG} stress rationalizes the limited channel migration (see Figure 4d). Figure 4e displays the field-effect mobility ($\mu_{FE} = g_m \cdot (L/W) \cdot C_{OX}^{-1} \cdot V_D^{-1}$) determined from the maximum value of g_m for both cases. Because of the additional oxide trap sites created, the μ_{FE} of pristine ReS₂ obtained is always larger than that of the stressed sample when V_D is less than 1 V. However, this observed difference in μ_{FE} mostly vanishes as V_D further increases ($V_D > 1$ V), reflecting the suppressed contribution of R_{Int} and the oxide trap sites to μ_{FE} and supporting the channel migration along the c -axis of the multilayer ReS₂. The I_D - V_D output characteristic and output transconductance curves as a function of V_{BG} further confirm this channel migration and carrier mobility enhancement (see Figure S3 in SI). This fact further

implies that the observed degradation of μ_{FE} is exclusively dominant for the bottom-channel of the ReS₂, leading us to conclude that there is a negligible stress effect on the ReS₂ channel itself comparing to that of SiO₂.

Figure 4. Turn-on voltage determination and carrier mobility enhancement. V_D normalized V_{BG} -dependent dg_m curves (a) before and (b) after the V_{BG} stress. Blue and red regions represent the second dg_m peak position in both cases as a function of V_D . (c) V_D -dependent V_T corresponding to top- and bottom-channels determined from the first and second maximum dg_m peak position, respectively. As V_D increases, the top- and bottom-channels merge together, and exhibit a single dg_m peak particularly when V_D is larger than 1 V. (d) V_T differences between the V_T obtained in Figure 4c as a function of V_D for both cases. (e) V_D -dependent μ_{FE} before (blue rectangular) and after (purple circle) the V_{BG} stress.

CONCLUSION

We clearly demonstrate the electric field-dependent conducting channel migration in 2D multilayer ReS₂ and its spatial restriction after V_{BG} stress is applied. The V_D - and V_{BG} -dependent R_{int} enables modulating the position of the maximum conducting channel along the c -axis of the ReS₂, which is further rationalized by the numerical calculation results by taking

into account the resistor network model and Thomas–Fermi charge screening theory. The oxide trap sites created after the occurrence of V_{BG} stress significantly degrades the carrier mobility and hampers the formation of the bottom channel inside the ReS_2 , resulting in a restricted channel migration. However, as V_D increases, the contribution of R_{Int} to the total carrier transport is considerably suppressed regardless of the V_{BG} stress, which consequently facilitates the channel migration toward the top channel and broadens the channel inside the multilayer ReS_2 by combining the top and bottom channels. This fact clearly indicates the stronger effects of the damaged oxide traps on the bottom channel formation rather than the top channel formation inside the ReS_2 . Our findings will be of significant help in the development of next-generation semiconductor electronic devices using 2D multilayer materials and will deepen our understanding of their charge transport behavior.

METHODS

Device Fabrication

Micromechanically exfoliated 1T' multilayer ReS_2 (purchased from 2D Semiconductors) flakes were first transferred onto a 90-nm SiO_2/p^+ -Si substrate using a conventional scotch type method. After finding an optimal ReS_2 flake with a thickness of ~ 11 nm using AFM (Nx-10, Park Systems), selective electron-beam lithography (MIRA3, TESCAN) was carried out to define the dimensions of the channel and electrodes. Au (≈ 100 nm) metal was deposited using an electron-beam evaporator (INFOVION). The geometrical channel length (≈ 1 μm) and width (≈ 0.614 μm) were also confirmed using AFM and an optical microscope (BX53M, Olympus). The optical Raman spectrum of a ReS_2 flake with a thickness of ≈ 11 nm was acquired using a LabRam ARAMIS IR2 system with a 532-nm laser source at a power of 5 mW. The frequency range used was 100–500 cm^{-1} at room temperature.

Electrical Characterization

All electrical measurements were conducted after an annealing process at 200 °C for 10 h in a high vacuum metal chamber ($\approx 10^{-6}$ Torr) using a commercial semiconductor characterization system (B1500A Keysight /4200-SCS Keithley). The fabricated ReS₂ device was first placed in a vacuum probe station. The transfer and output characteristic curves of the pristine ReS₂ device were obtained as a function of the V_D (from 10 mV to 5 V) and V_{BG} (from -50 V to 50 V) at room temperature. A constant V_{BG} of 60 V was then applied to the ReS₂ for 40,000 s to create numerous trap sites in the SiO₂. We repeated the same measurements to obtain the transfer and output characteristic curves after the stress was applied.

DATA AVAILABILITY

Data are available upon request.

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AUTHOR CONTRIBUTIONS

C.K. and M.-K.J. conceived and developed the study under the guidance of G.T.K. C.K., S.Y.K., Y.K., and Y.S. fabricated the device. C.K., M.S., B.C.L., and C.T. conducted the electrical measurements and characterized the data. D.K. and Y.K. analyzed the optical Raman properties. C.K., M.-K.J., and G.T.K. wrote the manuscript and discussed the final presentation with all of the authors.

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Competing interests

The authors declare no competing interests.

Supporting Information Supporting figures and discussion contains the interlayer resistivity of 2D ReS₂ confirmed by c-AFM measurement, the enhancement of gate leakage current after the electrical stress, and the I_D - V_D output characteristic and corresponding output transconductance curves as a function of V_{BG} , respectively. These materials further confirm the restricted channel migration and are available free of charge via the Internet at <http://pubs.acs.org>.

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