As the scaling of Si-based transistor approaches its limits, attention has been focused on new materials such as graphene and transition metal dichalcogenides (TMDs) for their applications in high-speed and low-power electronics. Although graphene has remarkably high carrier mobility, graphene field-effect transistors (FETs) show very low on/off current ratio which is at most the level of a few tens because of the lack of a band gap. TMDs in the form MX$_2$, where M represents a transition metal atom (e.g., Mo, W, Ti, Zr, Hf, Ta, and Nb) and X represents a chalcogen atom (e.g., S, Se, Te), have a band gap that can enable strong on/off current modulation. The X-M-X atoms in each layer are covalently bonded while layer stacks are coupled by van der Waals forces. In TMDs, the absence of surface dangling bonds, excellent gate control effects, dielectric-mediated mobility, and reduced short channel effects are all desirable electrical properties for transistor applications. In recent years, tunneling FETs (TFETs) based on vertical stacking of two dimensional materials have attracted great interests in the searching for low-power logic devices. In silicon TFETs, due to the large energy band gap, poor subthreshold swings (SS) and low on-current have hampered the practical applications. Alternative two-dimensional crystals with small band gaps of 0.5–1.0 eV and low effective masses are in demand to achieve a large on-current. Hf-based TMDs are predicted to be small band gap semiconductors with large work functions and high mobility which render them suitable materials for TFET applications. Recent density functional theory calculations show two interesting results, first, monolayer HfSe$_2$ is suggested to be a suitable p-type drain material and second, the electrical properties of Hf-based materials have a strong dependence on strain. For HfSe$_2$ even a 1% increase in the lattice parameter results in an increase of 0.1 eV in the band gap. HfSe$_2$ is an n-type semiconductor with an experimentally determined band gap of 1.1 eV for the bulk materials, while various theoretical calculations manifest the indirect band gap of 0.45 and 0.6. HfSe$_2$ crystallize in the layered 1T structure in which the transition metal is octahedrally coordinated by six chalcogenide atoms with the lattice parameters of a = 3.75Å and c = 6.16Å as shown in Fig. 1(a). In this study, we fabricated multilayer HfSe$_2$ FETs using exfoliated nanoflakes from bulk crystals and performed electrical measurements with these devices. Relatively high gate modulated current reaching ~µA was observed. We further analyze the temperature dependence of carrier transport behavior through mobility and Arrhenius plots. The results on the physical and electrical characterization of two dimensional HfSe$_2$ material demonstrate the feasibility of this semiconducting material for electronic devices.

The HfSe$_2$ flakes were produced by standard mechanical exfoliation using the scotch tape technique from a commercial bulk HfSe$_2$, synthesized by chemical vapor transport (CVT) method purchased from 2D semiconductors. The flakes were deposited on a silicon substrate with 285 nm SiO$_2$. The exfoliated flakes were identified using an optical microscope and characterized with both atomic force microscopy (AFM) and Raman spectroscopy. Figure 1(b) shows an optical image of thin flakes with the inset showing the AFM image of the dotted area. Figure 1(c) shows a line profile across the edge of the flake with a height of 17.3 nm (~28 layers). The Raman spectrum, which was taken at room-temperature using a 532 nm laser, as shown in Fig. 1(d), verifies the flake as HfSe$_2$. The A$_{1g}$ peaks at 199 cm$^{-1}$ is in good agreement with previously reported result.

The back-gated FET devices were fabricated by photolithography to define electrical contacts on selected flakes. Figure 2 show the optical images of a multilayer HfSe$_2$ field-effect transistor which was evaluated in this paper. The device had a channel length (L) of 3.6 µm and a channel width (W) of 4.4 µm. Figure 2(a) shows the Cr/Au electrodes...
deposited by electron beam evaporation of 10 nm Cr and 80 nm Au after standard lift-off process in acetone. While two-dimensional materials like MoS$_2$ and WSe$_2$ are comparatively stable, other materials such as black phosphorous are very sensitive to ambient environment, in particular, to oxygen and moisture, and change their properties within a few minutes of exposure. HfSe$_2$ is also sensitive and prone to ambient conditions, especially during measurements. Therefore, we have used polymethyl methacrylate (950 PMMA 6% in Anisole) passivation over the HfSe$_2$ flakes. The PMMA was spin-coated at a rate of 6000 rpm for 30 s and then annealed at 180°C on a hot plate for 5 min, as shown in Fig. 2(b).

The output and transfer characteristics of a FET fabricated on a 17.3 nm thick HfSe$_2$ flake (~28 layers) are shown in Fig. 3. Figure 3(a) shows a schematic diagram of the structure of HfSe$_2$ FET together with electrical connections. For measurements, the heavily n-doped Si substrate was used as a back gate to modulate the carrier density, the source contact was grounded and the drain contact was biased with the applied signal. We performed electrical characterization of our devices in vacuum using a Keithley 4200 semiconductor characterization system (4200-SCS). As HfSe$_2$ belongs to the family of TMD materials which exhibit a high photoresponse, all the measurements were carried out in dark conditions.

Figure 3(b) shows the output characteristics (drain current vs. drain voltage, $I_{ds}$-$V_{ds}$) measured at various back-gate voltages ($V_{bg}$) at 280 K. In contrast to what is expected in a conventional FET, the dependence of $I_{ds}$ on $V_{ds}$ is mostly linear, and it does not show saturation at high drain bias. Figure 3(c) shows the transfer characteristics (drain current vs. back-gate voltage, $I_{ds}$-$V_{bg}$) with a variation of drain voltage ($V_{ds}$) at 280 K. As the back-gate voltage is swept from $V_{bg} = -70$ to $+70$ V, the FET conduction channel switches from an insulating state to a conducting state. This n-type FET behavior is similar to previous works and is an evidence of electron doping in HfSe$_2$ materials. When a positive gate voltage is applied, electrons are accumulated in the channel so that the current $I_{ds}$ increases. At negative $V_{bg}$, electrons are depleted, the electrical conductance is suppressed. In Fig. 3(d), the magnitude of the current $I_{ds}$ is re-plotted on a semi-logarithmic scale as a function of $V_{bg}$. For negative gate voltage $V_{bg} < -70$ V, the FET device is in a completely depleted state with $I_{ds} = 8$ pA at $V_{ds} = 1$ V. The threshold voltage of this device, $V_T = ~24$ V does not appear to change noticeably with $V_{ds}$, which is in consistent with the behavior of a long-channel device. The on/off current ratio is found to exceed $5.1 \times 10^5$ at 280 K as shown in Fig. 3(d).

We demonstrate the temperature dependence of the HfSe$_2$ FET output and transfer characteristics to better understand the device physics in Fig. 4. At low temperatures, the thermally excited carrier concentration is reduced and the device becomes much more resistive as expected for a typical semiconductor, as shown in Figs. 4(a) and 4(b). The field-effect mobility can be extracted as $\mu = (L/W) \times (g_m/C_{ox} V_{ds})$, where $L = 3.6 \mu$m is the channel length, $W = 4.4 \mu$m is the channel width, and $C_{ox}$ is the dielectric capacitance per unit area between the channel and the back gate, calculated by using $C_{ox} = \varepsilon_0 \varepsilon_r /d$ in which $\varepsilon_r$ ($=3.9$) is the relative permittivity of SiO$_2$, $\varepsilon_0$ ($=8.854 \times 10^{-12}$ F·m$^{-1}$) is the free-space permittivity and $d$ is the SiO$_2$ thickness. The value of $C_{ox}$ for 285 nm SiO$_2$ substrate is $1.2 \times 10^{-4}$ F·m$^{-1}$ and the transconductance, $g_m = (dI_{ds}/dV_{bg})$, is determined by the slope extracted from the experimental data in Fig. 4(b). The device has a high on/off current ratio exceeding $7.5 \times 10^6$ at 120 K as shown in Fig. 4(b). Figure 4(c) shows the temperature dependence of mobility for the same device presented in Fig. 2(b). We observe a
monotonous increase of the mobility as the temperature is decreased from room temperature and then it shows saturation at lower temperatures. The mobility at 280 K is $0.22 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$ and increases with decreasing temperature. At temperatures lower than 200 K, the temperature dependence of the mobility becomes very weak until it saturates at $0.38 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1}$ at 120 K. In the temperature range of 200 K–300 K, the temperature dependence shows $\mu \sim T^{-1.99}$, which is in good agreement with the previous reports for other 2D TMD materials when electron-phonon scattering is the dominant scattering mechanism. The observed low field-effect mobility in this study can be attributed to various reasons, for example, the high anisotropic effective mass of HfSe$_2$ can limit the vertical transport in the ohmic region, the barrier at non-ideal ohmic contacts, and the environmental instability of HfSe$_2$ crystal in the ambient condition. We have also observed metal-insulator-transition (MIT) at a back-gate voltage of $\sim 63 \, \text{V}$, corresponding to a critical carrier density ($n_c$) of $\sim 1.8 \times 10^{12} \, \text{cm}^{-2}$ as shown in Fig. 4(b). The carrier density is calculated using $n_c = \frac{C_{ox} (V_{bg} - V_{th})}{e}$, where $e = 1.602 \times 10^{-19} \, \text{C}$ is the elementary charge and $V_{th}$ is the threshold voltage of 39 V at 220 K. Recent results on MoS$_2$ and MoSe$_2$ have also shown that the critical carrier density for MIT varies from $10^{12}$ to $10^{13} \, \text{cm}^{-2}$. In addition to the dependence on the number of layers, these variations in critical concentration can also be explained by the percolation transition model where the density inhomogeneities of

![FIG. 3. (a) Schematic diagram of HfSe$_2$ FET together with electrical connections. (b) Output characteristics ($I_{ds}$-$V_{ds}$) with various back-gate voltages at 280 K. Transfer characteristics ($I_{ds}$-$V_{bg}$) of HfSe$_2$ FET for various drain voltages in linear scale (c) and semi-logarithmic scale (d) at 280 K, respectively.]

![FIG. 4. (a) Temperature dependence of HfSe$_2$ FET output characteristics ($I_{ds}$-$V_{ds}$) with a fixed $V_{bg} = 20 \, \text{V}$. (b) Temperature dependence of HfSe$_2$ FET transfer characteristics ($I_{ds}$-$V_{bg}$) with a fixed $V_{ds} = -3 \, \text{V}$. The inset shows the magnitude of $I_{ds}$ re-plotted in a semi-logarithmic scale as a function of $V_{bg}$. (c) Field-effect mobility $\mu$ as a function of temperature $T$. (d) Arrhenius plots for various back gate voltages with a fixed $V_{ds} = -3 \, \text{V}$.]

the electron states due to impurities and defects play a significant role in determining the critical concentration.\textsuperscript{24} As can be seen from Fig. 4(b), for carrier density less than $n_c$, the system behaves like a semiconductor as drain current decreases with decreasing temperature.\textsuperscript{23} This manifestation of MIT point refers to the strongly correlated behavior of the 2D electron gas. It may be noted that although the thickness of the HfSe$_2$ flake used in the device is 17.3 nm ($\approx$28 layers), the current is confined in 1–2 nm thick region near the back-gate dielectric interface which resulted in the observation of 2D quantum transport behavior.\textsuperscript{26} Figure 4(d) shows an activation behavior for the temperature range from 120 to 280 K. The resistance can be well fitted by the Arrhenius equation, $R = R_0 \exp \frac{E_a}{k_BT}$, where $E_a$ is the activation energy, $k_B$ is the Boltzmann constant. The resistance ($R$) is determined from the linear region of the $I_{ds} - V_{ds}$ curves at different temperatures. In Fig. 4(d), $R$ is plotted on a natural-logarithmic scale as a function of 1000/T. The good agreement of data with the activation transport model is suggestive of thermally activated charge transport at temperatures higher than 200 K. At $T \leq 200$ K we find that the variation of $R$ weakens for almost all $V_{bg}$ values. This can be explained with hopping through localized states becoming dominant at lower temperature, driving the system into a strongly localized regime.\textsuperscript{23,24,26}

In summary, we have fabricated and characterized HfSe$_2$ based n-type two-dimensional field-effect transistors with a high on/off current ratio exceeding $7.5 \times 10^{6}$ and a mobility of 0.38 cm$^2$ V$^{-1}$ s$^{-1}$. The observation of MIT at $n_c \sim 1.8 \times 10^{12}$ cm$^{-2}$ demonstrates the strongly correlated transport behavior in these devices. Further improvements in the ohmic contacts and improved passivation techniques hold the key for enhancement in the mobility. Our results demonstrate that HfSe$_2$, a layered two-dimensional semiconductor with a finite band gap, is a promising 2D material for future digital electronics.

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\textsuperscript{7}N. Ma and D. Jena, \textit{Appl. Phys. Lett.} 102, 132102 (2013).
\textsuperscript{21}See supplementary material at http://dx.doi.org/10.1063/1.4917458 for details of the time-dependent and joule-heating induced degradation, and photoresponse of exfoliated HfSe$_2$ flakes on SiO$_2$ substrate.