High-Current Gain Two-Dimensional MoS₂-Base Hot-Electron Transistors

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* Supporting Information

ABSTRACT: The vertical transport of nonequilibrium charge carriers through semiconductor heterostructures has led to milestones in electronics with the development of the hot-electron transistor. Recently, significant advances have been made with atomically sharp heterostructures implementing various two-dimensional materials. Although graphene-base hot-electron transistors show great promise for electronic switching at high frequencies, they are limited by their low current gain. Here we show that, by choosing MoS₂ and HfO₂ for the filter barrier interface and using a noncrystalline semiconductor such as ITO for the collector, we can achieve an unprecedentedly high-current gain (α ∼ 0.95) in our hot-electron transistors operating at room temperature. Furthermore, the current gain can be tuned over 2 orders of magnitude with the collector-base voltage albeit this feature currently presents a drawback in the transistor performance metrics such as poor output resistance and poor intrinsic voltage gain. We anticipate our transistors will pave the way toward the realization of novel flexible 2D material-based high-density, low-energy, and high-frequency hot-carrier electronic applications.

KEYWORDS: 2D materials, transition metal dichalcogenides, MoS₂, hot-electron transport, high-current gain

For over half a century, Moore’s law has driven the silicon electronics industry toward smaller and faster transistors. However, as the scaling limit of silicon complementary metal–oxide-semiconductor (CMOS) technology draws to an end, novel materials and device concepts have been eagerly sought out and investigated with hopes to augment the next generation of information processing. One promising device concept is the hot-electron transistor (HET),1−7 which relies on the vertical transport of a controlled source of hot-electrons. Ever since Mead first proposed this device concept in 1960,1,2 there have been plethora of HET variants implementing diverse material systems.1−7 Usually, these HETs feature substantial current gain (α ∼ 0.75) at cryogenic temperatures (T = 4.2 K) but very poor current gain at room temperature.3,4 Only a few HETs have shown high current gain (α ∼ 0.9) at room temperature,6−7 but rely on precise yet complicated epitaxial layered structures grown by molecular beam epitaxy (MBE). HETs implementing two-dimensional (2D) materials,8−10 such as graphene,8−10,11−12 in the base region13−15 have recently shown great promise for ultrahigh frequency operation.16−21 These vertical transport three-terminal electronic devices can be designed with atomically sharp heterostructures by the stacking of various van der Waals materials.9 This allows one to play with the conduction and valence band offsets,22 which determine the potential landscape experienced by hot-carriers and ultimately the device performance.23 Until now, only vertical graphene-base hot-electron transistors have been experimentally demon-
Yet their transport characteristics feature a significantly low common-base current gain ($\alpha \sim 10^{-2}$). These shortcomings preclude the fulfillment of realizing 2D material-based vertical hot-carrier transistors operating at high frequencies. As a first step toward this goal, we propose and demonstrate a novel device concept which enables unprecedentedly high current gain in 2D material-based hot-electron transistors. In this Letter, we demonstrate a novel vertical hot-electron transistor incorporating single-layer MoS$_2$ in the base region (MoS$_2$-HET). To the best of our knowledge, all previous vertical graphene-base hot-electron transistors implemented a metal for the collector electrode and exhibited an extremely low current gain. In this work, by utilizing a noncrystalline semiconductor such as ITO (an n-type transparent conducting oxide) as the collector electrode, we demonstrate for the first time that the MoS$_2$-HETs operate at room temperature and exhibit a high common-base current gain ($\alpha \sim 0.95$) over the entire base-emitter bias ($V_{BE}$) range.

Figure 1. Device structure and schematic of the MoS$_2$-HET. (a) An isometric view of an MoS$_2$-HET device structure. The capital letters E, B, and C represent the emitter, base, and collector, respectively. (b) Cross-sectional view of the vertical heterostructure active region with single-layer MoS$_2$ (0.65 nm) as the base, ITO ($\sim$45 nm) serves as the collector electrode, and an n$^{++}$ silicon substrate is used as the emitter. A thin SiO$_2$ ($\sim$3 nm) tunnel barrier is utilized for hot-electron injection, and HfO$_2$ ($\sim$55 nm) serves as the filtering barrier. The hot-electrons injected from the emitter (red arrows) are schematically shown. (c) Optical micrograph (top-view) of an actual MoS$_2$-HET device. The scale bar is 100 $\mu$m. The dashed circle outlines the MoS$_2$ region. (d) Common-base configuration circuit incorporating the schematic symbol for the MoS$_2$-HET device.
in order to confirm the consistent high-current gain results presented in this work.

In order to clearly understand the physics, we first focus on describing the two modes of operation for the MoS$_2$–HET using energy band diagrams. The flat band condition is shown in Figure 2a. The conduction band offset between the monolayer MoS$_2$ and HfO$_2$ is 1.52 eV. This forms the filter potential barrier height ($\Delta_e$) for the hot-electrons. The filter potential barrier height and width at the collector-base junction are important parameters that determine the collector current after the hot-electrons tunnel through the 3 nm SiO$_2$ emitter-base tunnel barrier. In the previous graphene-base hot-electron transistors, the filter barrier height between graphene and Al$_2$O$_3$ was 3.3 eV, whereas between graphene and HfO$_2$ it was 2.05 eV. In both prior cases, the filter barrier heights are greater than that between MoS$_2$ and HfO$_2$ (1.52 eV), thus an improvement of the ratio, in our case, between the collector current and the emitter current ($\alpha = I_C/I_E$) is expected.

The tunneling current across a tunnel junction is generally described by

$$I(V) \propto \int dE \rho_1(E) - \rho_2(E - eV) \cdot [f(E - eV) - f(E)] \cdot T(E)$$

where $f(E)$ is the Fermi distribution function, $\rho_1(E)$ is the density of states of the first electrode, $\rho_2(E)$ is the density of states of the second electrode, and $T(E)$ is the transmission probability which, for the MoS$_2$–HET device structure, is dominated by its exponential sensitivity to the barrier height ($\Delta_e$) as opposed to the tunneling density of states. $T(E)$ depends on the energy $E$ of the tunneling electrons as follows:

$$T(E) \sim e^{-W(E)}$$

where $W(E)$ is related to the effective width and height of the potential barrier and strongly depends on the strength of the electric field. $W(E)$ can be generalized within the WKB approximation:

$$W = 2 \int_0^d dx \cdot \Im k_i(\Delta(x))$$

Thus, the application of a strong electric field can dramatically alter the shape (e.g., both the effective height and width) of the potential barrier and result in an increased collector current. Moreover, when designing vertical hot-electron transistors, it is paramount to choose the proper combination of 2D material for the base as well as the filtering barrier dielectric, which yields the desired conduction band offset or filter potential barrier height, for the hot-electrons. Instead of relying on complicated and expensive

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**Figure 2.** Energy band diagrams for the operating conditions of the MoS$_2$–HET. (a) Flat band condition. Note that the conduction band offset, or the filter barrier height for the hot-electrons ($\Delta_e$), between the single-layer MoS$_2$ and the HfO$_2$ is $\Delta_e = 1.52$ eV. (b) The current components are depicted for the hot-electron contribution (red dotted arrow) to the total current. (c) Energy band diagram depicting the off-state condition. Electrons have insufficient kinetic energy to overcome the filter barrier at the collector-base junction and do not reach the collector. (d) Energy band diagram depicting the on-state condition. For $V_{CB} > 0$ (dashed red lines), the hot-electrons tunneling through the emitter-base tunnel barrier have sufficient kinetic energy to overcome the filter barrier and reach the collector.
methods to produce atomically sharp interfaces,\(^1\) it is now possible to design the equilibrium filter potential barrier height in vertical transport devices by choosing from plethora of 2D materials since the conduction band offset results from material specific parameters such as the electron affinity of the collector-oxide and the work function (e.g., in the case of graphene) or electron affinity (e.g., for all other 2D materials with bandgaps) of the particular 2D material used.

Having established the significance of the filter potential barrier height for the hot-electrons (\(\Delta_f\)) in the MoS\(_2\)−HETs, we next illustrate the current components governing the device transport. The current components for the hot-electron contribution (red arrow) to the total current flow through the MoS\(_2\)−HET are shown in Figure 2b. The emitter current (\(I_E\)) across the SiO\(_2\) tunnel oxide is due to hot-electrons injected from the n\(^{++}\) silicon substrate. Furthermore, the collector current (\(I_C\)) across the HfO\(_2\) collector-base oxide is due to the portion of the injected hot electrons with enough kinetic energy that surpass the filter barrier and reach the collector.

Now that the current components and the barrier heights experienced by the hot-electrons in the MoS\(_2\)−HETs have been shown, we proceed to describe the modes of operation of these novel transistors. Figure 2c shows the energy band diagram for the off-state condition of the MoS\(_2\)−HET. In the absence of an applied \(V_{CB}\), the hot-electrons injected through the tunnel oxide have insufficient kinetic energy to overcome the filter barrier at the collector-base junction and do not reach the collector. Instead, they backscatter and thermalize into the MoS\(_2\) base region. However, the situation drastically changes with the application of a large positive \(V_{CB}\). Figure 2d shows the energy band diagram for the on-state condition of the MoS\(_2\)−HET. In this scenario, hot-electrons tunneling through the emitter-base tunnel oxide have sufficient kinetic energy to overcome the filter barrier and reach the collector.

Based on the physical concepts just described, the device performances of the MoS\(_2\)−HETs were characterized using the common-base configuration. In the following, we characterize the MoS\(_2\)−HET by applying positive \(V_{CB}\). Figure 3a shows the energy band diagram depicting the MoS\(_2\)−HET. Specifically, Figure 3a shows the conduction and valence band edges at the collector-base junction with a positive \(V_{CB}\) applied. In this condition, once hot-electrons tunneling through the emitter-base tunnel barrier have sufficient kinetic energy, they can vertically transport through the MoS\(_2\) base region, surpass the filter barrier at the collector-base junction, and reach the collector. Consequently, an increasingly positive \(V_{CB}\) will continue to effectively make the filter potential barrier thinner and promote hot-electrons reaching the collector due to an increase in their transmission probability. This qualitative behavior is exhibited in the input and transfer characteristics of the MoS\(_2\)−HETs. The input characteristics (\(I_E-V_{BE}\)) correspond to how the emitter current depends on \(V_{BE}\) whereas the transfer characteristics (\(I_C-I_{BE}\)) correspond to the manner in which the collector current varies with \(V_{BE}\). Figure 3b shows the input and transfer characteristics for Device 1. In this device, the maximum \(V_{BE}\) is limited to 3 V to avoid dielectric breakdown of the tunnel oxide. The emitter current (\(I_E\)) and the collector current (\(I_C\)) are shown as a function of \(V_{BE}\) (\(V_{BE}\) was swept from 0 to +3 V) at a \(V_{CB}\) of +1 V. Both currents

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**Figure 3.** Electrical characterization of the MoS\(_2\)−HET in the common-base configuration. (a) Energy band diagram depicting MoS\(_2\)−HETs. The conduction and valence band edges at the collector-base junction are shown for a positive \(V_{CB}\), which reduces the filter barrier for the hot-electrons. (b) Input and transfer characteristics for Device 1. The emitter current (black diamonds) and the collector current (red circles) are shown as a function of \(V_{BE}\) at \(V_{CB} = +1\) V. (c) Transfer characteristics. The collector current as a function of \(V_{BE}\) is shown for various positive \(V_{CB}\). (d) Common-base current gain (\(\alpha\)) as a function of \(V_{BE}\) at \(V_{CB} = +8\) V. The inset shows \(\alpha\) as a function of \(V_{BE}\) at various positive \(V_{CB}\): \(V_{CB} = 0, +2, +4, +6,\) and +8 V.
rapidly increase at larger \( V_{BE} \), as is typical for HETs. Similarly, Figure 3c shows a family of transfer characteristics for Device 1. The collector current as a function of \( V_{BE} \) is shown for various positive \( V_{CB} \). It is evident that the collector current increases with increasingly positive \( V_{CB} \). This is due to the fact that the filter potential barrier width at the collector-base junction is effectively reduced as the applied \( V_{CB} \) becomes more positive. Correspondingly, a greater portion of the injected hot-electrons from the emitter have high enough kinetic energy to vertically transport through the MoS\(_2\) base region, surpass the filter barrier, and reach the collector, thus contributing to an increasing collector current.

From the input and transfer characteristics, we can next ascertain the common-base current gain (\( \alpha \)) of Device 1, which is a figure of merit for HETs and is defined as \( \alpha = I_C/I_E \). Figure 3d shows \( \alpha \) as a function of \( V_{BE} \) at \( V_{CB} = +8 \) V. Interestingly, the current gain, \( \alpha \), features a nearly constant characteristic throughout the entire \( V_{BE} \) range with an average magnitude of about 95\% at \( V_{CB} = +8 \) V.

With the analysis of the input and transfer characteristics complete, we now investigate the common-base output characteristics of the MoS\(_2\)−HETs, which correspond to how the output collector current depends on \( V_{CB} \). Figure 4a shows the common-base output characteristics for Device 2. The collector current is shown as a function of \( V_{CB} \) at three positive \( V_{BE} \) biases. The collector current is insensitive to modulation below a critical electric field, or correspondingly a \( V_{CB} \) voltage, across the HfO\(_2\) collector-base oxide. However, above a critical electric field across the HfO\(_2\), the collector current is quite sensitive to modulation and rapidly increases with a further increase in \( V_{CB} \).

Figure 4. Output characteristics and tunable current gain of the MoS\(_2\)−HET. (a) Common-base output characteristics for Device 2. The collector current is shown as a function of \( V_{CB} \) at \( V_{BE} = +1 \) V, +2 V, and +3 V. (b) The common-base current gain (\( \alpha \)) for Device 2 is shown in log-scale as a function of \( V_{CE} \) for \( V_{BE} = +3 \) V.

With the robust nature of this high current gain in the MoS\(_2\)−HETs, Figure 4b shows a semilog plot of \( \alpha \) as a function of \( V_{CB} \) at \( V_{BE} = +3 \) V. It clearly shows that \( \alpha \) increases with an increasingly positive \( V_{CB} \) and can be tuned over an order of magnitude since this lowers the filter potential barrier experienced by the hot-electrons and allows them to reach the collector. Remarkably, the room temperature
common-base current gain ($\alpha$) in this type of novel 2D material-based vertical device is unprecedentedly high for the largest $V_{CB}$ applied.

Next, we investigate the MoS$_2$-HET characteristics when biased in the common-emitter configuration in order to corroborate the high and tunable current gain we achieved in the common-base configuration. The Gummel plot is used as a figure of merit when analyzing bipolar transistors. It is a simultaneous semilog plot of the collector and base currents as a function of the input voltage ($V_{BE}$) at a fixed output voltage ($V_{CE}$). The common-emitter current gain ($\beta = I_C/I_B$) can be ascertained from the Gummel plot by taking the ratio of the collector current to the base current at a fixed $V_{RE}$. Figure 5a shows the Gummel plot for Device 1 when biased in the common-emitter configuration.

The collector and base currents are shown in log-scale as a function of $V_{BE}$ at a fixed output voltage of $V_{CE} = +10$ V. The Gummel plot confirms the transistor action of the MoS$_2$-HET as the input base current is directly amplified to the output collector current. Finally, Figure 5b shows the common-emitter output characteristics for Device 1. The collector current is shown as a function of $V_{CE}$ at three positive $V_{BE}$ biases in addition to $V_{BE} = 0$ V. The inset shows the common-emitter current gain ($\beta$) as a function of $V_{CE}$ at $V_{BE} = +2$ V. A maximum common-emitter current gain of around 4 is achieved, and it can be tuned with the output voltage $V_{CE}$. We note that a slightly different current gain is obtained between the common-emitter and the common-base configuration measurements. We speculate that this discrepancy is due to the differences in the measurement circuits biasing the actual device structure in the two measurement configurations. Applying an output voltage ($V_{CE}$) in the common-base configuration results in the collector current originating from the ITO collectore electrode, traversing through the HfO$_2$ filter barrier dielectric, and laterally transporting through the MoS$_2$ surface into the grounded base contacts. This is because $V_{CB}$ actually only controls the band bending of the HfO$_2$ layer, and it does not modulate the SiO$_2$/MoS$_2$ layers due to the fact that our base contacts lie on the top surface of the MoS$_2$. Thus, $\alpha$ is mainly limited by the recombination processes inside the HfO$_2$ dielectric, which is quite small. However, applying an output voltage ($V_{CE}$) in the common-emitter configuration results in the collector current traversing through the entire ITO/HfO$_2$/MoS$_2$/SiO$_2$/p$^+$ silicon vertical heterostructure, since band bending occurs throughout the entire heterostructure. Furthermore, since there exist more pronounced non-radiative recombination (e.g., Auger recombination and trap-states) processes in the MoS$_2$ layer, the measured $\beta$ in the common-emitter configuration is thus expected to be smaller than the measured $\alpha$ in the common-base configuration. Nonetheless, by biasing the MoS$_2$-HETs in both the common-base and the common-emitter configurations, we have explicitly shown that the measured current gains ($\alpha$, $\beta$) in either scenario corroborate each other and further attest the high and tunable current gain in our MoS$_2$-HETs.

On the other hand, for transistor operation, it is better to operate in the saturation region of the output characteristics where the collector current ($I_C$) is fairly constant. However, the lack of any reasonable saturation in the output characteristics of the MoS$_2$-HETs (see Figure 3b) may be due to the onset of dielectric breakdown in both the SiO$_2$ tunnel oxide and the HfO$_2$ filter oxide. The lack of saturation in the output characteristics is specific to this batch of MoS$_2$-HETs but may be achieved if a filter oxide with a larger dielectric strength and/or a reduced thickness is used in order to promote larger accelerating electric fields across the filter oxide. In fact, the current gain dependence on $V_{CB}$ indicates that the output resistance and the intrinsic voltage gain of our MoS$_2$-HETs are poor. Based on our measurements, the input and output resistances are on the order of a G$\Omega$ and a few tens of G$\Omega$, respectively. The intrinsic voltage gain in these prototype MoS$_2$-HETs is around 3, which is quite small. In order to improve the intrinsic voltage gain, a low input impedance is desirable. In our device structure, a low input impedance can be readily achieved by further reducing the thickness of the SiO$_2$ tunnel barrier to around 1 nm. The ensuing tunneling current density ($I_B$) should improve by at least 2 orders of magnitude and thus enable a much higher intrinsic voltage gain in our MoS$_2$-HETs. Furthermore, reducing the thickness of the tunnel oxide would significantly benefit the driving capability and speed of the MoS$_2$-HETs compared to the current batch which feature very small device current levels. It is worth mentioning that the MoS$_2$-HETs in this work were intentionally designed for DC electrical characterization in order to prove that decreasing the filter potential energy barrier height using MoS$_2$ and HfO$_2$ (e.g., 1.52 eV) from the previous higher filter potential energy barrier heights (e.g., 3.3 eV for graphene/Al$_2$O$_3$ and 2.05 eV for graphene/HfO$_2$) greatly improves the current gain. Presently, our prototype MoS$_2$-HETs are not optimized in terms of their device layout and material parameters (e.g., tunnel and filter oxide thickness) for high frequency operation. Their estimated cutoff frequency ($f_T$) and maximum oscillation frequency ($f_{max}$) as calculated using the equations $f_T \sim 1/(2\pi\tau_{BC})$ and $f_{max} \sim (\pi R_C C_{BC})^{1/2}$, which is 7.6 MHz for the $f_T$ and 1.1 MHz for the $f_{max}$ respectively. The $\tau_{BC}$ is the RC time constant. The RC for the two junctions is from the resistance we assumed ($R_C = 50$ Ohms), and the calculated parallel plate capacitance ($C_{BE} = 300$ pF and $C_{BC} = 120$ pF) between the base and other electrodes according to the device structure. The MoS$_2$-HETs may be further optimized for high frequency performance by properly engineering the following device parameters: a reliable and pinhole-free tunnel barrier with low barrier height (e.g., conduction band offset) and thin barrier width, minimizing the base resistance of MoS$_2$, and minimizing the parasitic capacitances throughout the device structure.

In conclusion, we have demonstrated a novel vertical hot-electron transistor incorporating single-layer MoS$_2$ in the base region. This MoS$_2$-HET operates at room temperature and exhibits an unprecedentedly high common-base current gain $\alpha$ of about 0.95 over the entire $V_{BE}$ bias range, which can be dynamically tuned around 2 orders of magnitude by varying $V_{CB}$. We reiterate the fact that this current gain dependence on $V_{CB}$ is detrimental in terms of transistor performance metrics (e.g., poor output resistance and poor intrinsic voltage gain) but it is a novel phenomenon inherent to our prototype MoS$_2$-HETs and worth investigating. The majority of the fabrication process was designed to be compatible with CMOS technology. All things considered, there exist several features of this prototype transistor which can benefit from further optimization. First, its low tunneling current density ($I_B \sim 10$ mA cm$^{-2}$) can be improved around 2 orders of magnitude by reducing the SiO$_2$ tunneling barriers to be about 1 nm. High current levels in addition to high-current gain are essential toward realizing high-frequency applications in the future. Second, the hetero-
structure materials used in this work can be extended to other material combinations to further enhance the performance as well as functionalities. By implementing different 2D materials for the emitter-base tunneling barrier (e.g., hexagonal boron nitride), base (e.g., other transition metal dichalcogenides), and collector (e.g., graphene) on flexible substrates, a new family of flexible hot-carrier electronics could emerge. Third, the presently high base resistance of the MoS$_2$ base region could be reduced by phase engineering the MoS$_2$ from its semiconducting 2H phase to its metallic 1T phase.$^{39}$ Although very little is known about the exact vertical transport behavior in CVD single-layer MoS$_2$, which promotes the scalability and optimization of the device layout and structure as well as the potential for potentially higher frequency applications. Thus, the further base region for high-current gain or graphene in the base region could promote the scalability and potential commercialization of such devices.$^{35}$

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