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# High Performance Short Channel Field Effect Transistors Based on 2D Materials with Ohmic Contacts

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Final Report



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**14. ABSTRACT**
We have built on our discovery of achieving clean contacts using indium as the contact metal. In addition, we have begun to tune the metal deposition method achieve clean interfaces between refractory metals with high work functions and 2-D semiconductors to achieve p-type contacts. Our very recent results suggest it is possible to create clean vdW contacts via direct deposition of high work function metals on single TMD semiconductors (Fig. 5). Our strategy is to use a very low deposition rates and substrate cooling down to 77K to eliminate damage and chemical reactions.

**15. SUBJECT TERMS**
transistor, 2-dimensional material, semiconductor, electrical contact

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High Performance Short Channel Field Effect Transistors Based on 2D Materials with Ohmic Contacts

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FINAL REPORT

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In the final report of the project, we have built on our discovery of achieving clean contacts using indium as the contact metal. In addition, we have begun to tune the metal deposition method achieve clean interfaces between refractory metals with high work functions and 2D semiconductors to achieve p-type contacts. Below, I summarize our findings from the project.

**Ultraclean Van Der Waals Contacts**

We wanted to extract the Schottky barrier height of indium contacts on various 2D semiconductors. Below is a detailed description of the methodology we utilized to achieve this. TLM results of In/Au contacted few-layered $MoS_2$ are given in Figure 1a. The contact resistance extracted is 800 Ω·µm. As shown in Figure 1b, the contact resistance decreases with increasing carrier concentration for In/Au electrodes. The reported results of contact resistance of Sc, Ti and Au electrodes deposited in ultra-high vacuum ($10^{-9}$ Torr) are included for comparison. Comparison of contact resistance from literature for different types of electrode materials is given in Figure 1c, which shows In/Au contact gives lowest contact resistance results. Typical transfer curve of the In/Au contacted device shows good ON/OFF ratio and high current density. The output curve at room temperature shows that the highest current density is 196 µA/µm. More importantly, the output characteristics at low temperature also shows linear output characteristics indicating the absence of a contact barrier. Because charge injection strongly depends on the Schottky barrier height, knowledge of its value allows us to understand how electrons/holes are transported at the contacts. The most common way of extracting the Schottky barrier height is measuring the activation energy in the thermionic emission region. The reversed biased contact consumes most of the applied voltage and dominates the transistor behavior. The current density is determined by:

$$J = A^{*}T^{\alpha} \exp\left[-\frac{q\,\Phi_{B0}}{k_B T}\right]\left[1 - exp\left(-\frac{qV}{k_B T}\right)\right]$$

where A* is the Richardson constant, $\Phi_{B0}$ is the Schottky barrier height, α is an exponent equal to 2 for bulk semiconductors and 3/2 for 2D semiconductors, V is the applied bias, T is temperature and $k_B$ is the Boltzmann constant. For qV >> $k_B T$, the equation simplifies as:

$$J = A^{*}T^{\alpha} \exp\left[-\frac{q\,\Phi_{B0}}{k_B T}\right]$$

To extract the Schottky barrier height, we identify the voltage at which $\Phi_{B0}$ stops depending linearly on Vg, as shown in Figure 2b. Measurements as a function of temperature reveal Schottky barrier height to be around 110 meV, which is consistent with work function of the metal and conduction band energy level of $MoS_2$. Measurements of mobility with temperature reveals that the phonon-limited mobility scales as $\mu \propto T^{-1}$ at low temperatures and as $\mu \propto T^{-1.6}$ at high temperatures because of acoustic phonon scattering.

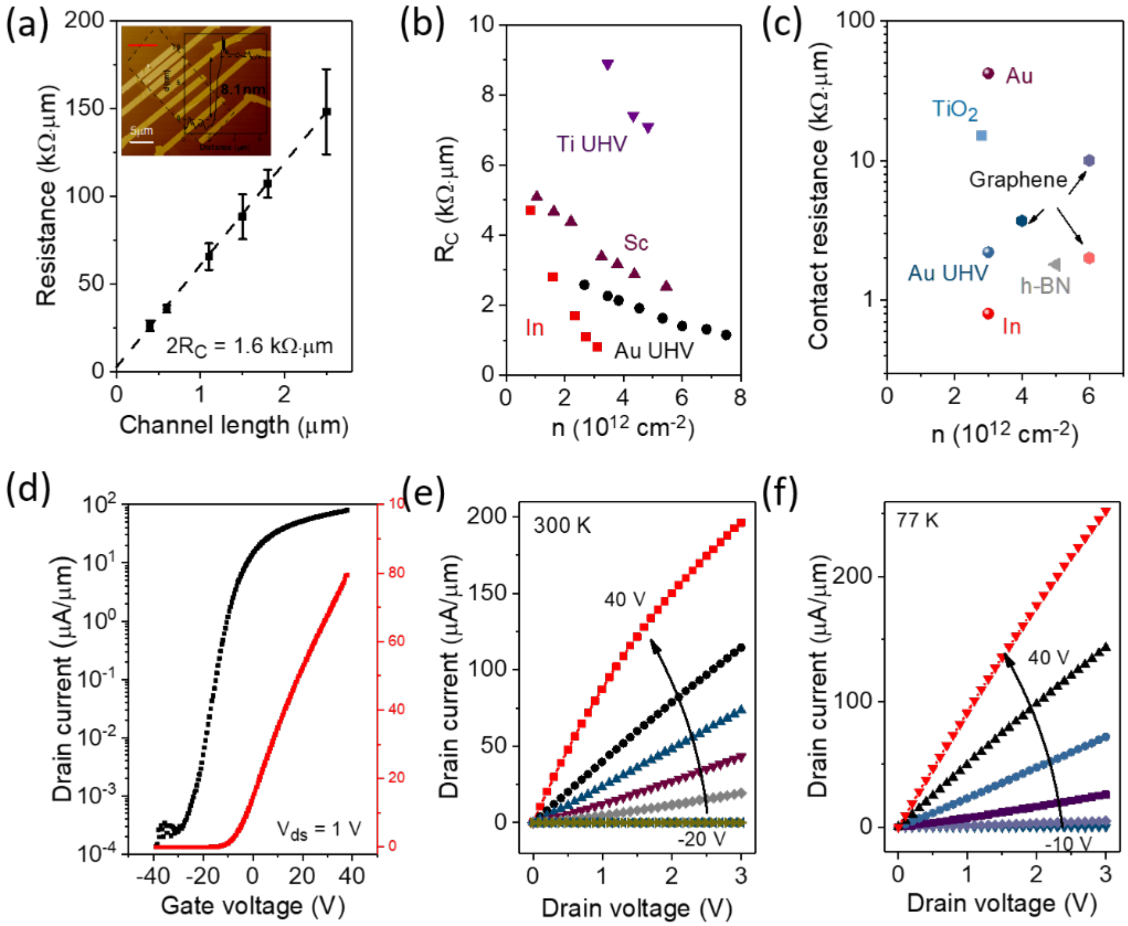


Figure 1: (a) TLM results of In/Au contacted few-layered $MoS_2$. Insert is the AFM image of the device. (b) Contact resistance versus carrier concentration for In/Au electrodes. Sc, Ti and Au electrodes deposited in ultra-high vacuum ($10^{-9}$ Torr) are provided for comparison. (c) Comparison of contact resistance from literature and our results for different types of electrode materials. (d) Typical transfer curve at room temperature shows good ON/OFF ratio. (e) Typical output curve at room temperature shows that the highest current density is 196 µA/µm. (f) Output characteristics at low temperature, linear output characteristics indicating the absence of a contact barrier.

Contact resistance of few-layered $MoS_2$ are extracted by TLM at different temperature. Figure 3 shows the contact resistance decreases with increasing testing temperature. The sheet resistance ($R_{SH}$) is extracted from the slop of the TLM plot. The result shows that $R_{SH}$ increases with increasing test temperature. The interfacial contact resistivity and transfer length are defined by the following equation:

$$\rho_C = \frac{(R_C W)^2}{R_{SH}}$$

$$L_T = \sqrt{\rho_C / R_{SH}}$$

At 300 K the lowest effective contact resistivity is $\rho_C \approx 1 \times 10^{-7}$ Ω·cm$^2$ for In/Au contacts. This result is comparable to that of chemically doped contacts, but without the disadvantage of a highly doped channel. $\rho_C$ decreases with increasing T due to increased thermionic emission. The extracted $L_T$ is around 10 - 20 nm at 300 K, a relatively small value consistent with a large $R_{SH}$ and small $\rho_C$. The transfer length rapidly decreases with rising temperature, as $R_{SH}$ increases due to phonon scattering and $\rho_C$ decreases from enhanced thermionic emission.

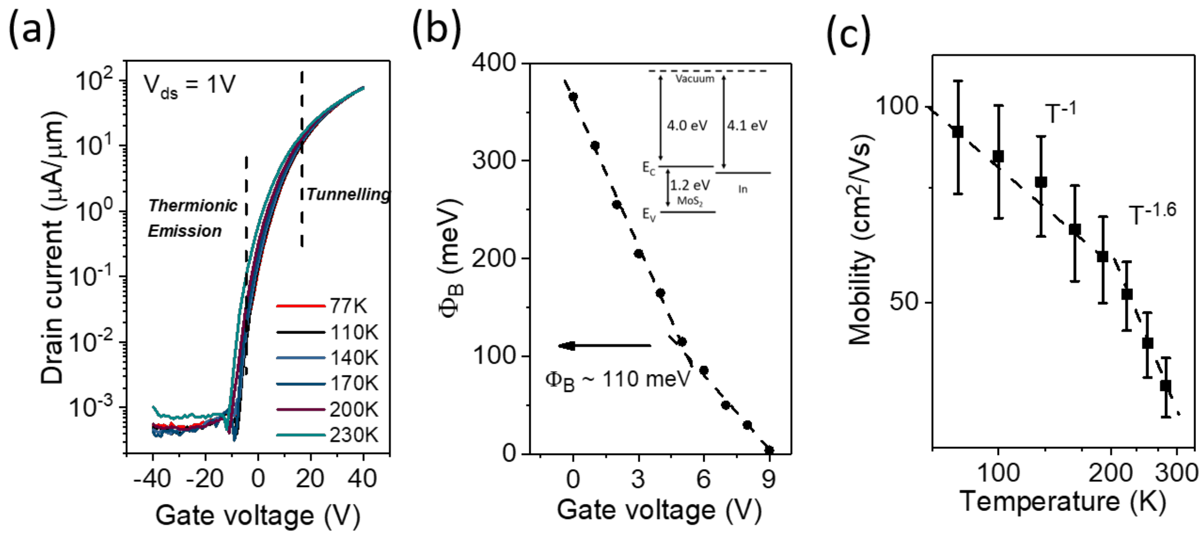


Figure 2: (a) Transfer characteristics with temperature showing metal-insulator transition. (b) Schottky barrier extraction indicating ideal In contacts with $MoS_2$, inset is energy band diagram of Indium metal and $MoS_2$. (c) Mobility versus temperature reveals phonon-limited property at low temperature and acoustic phonon scattering at high temperature.

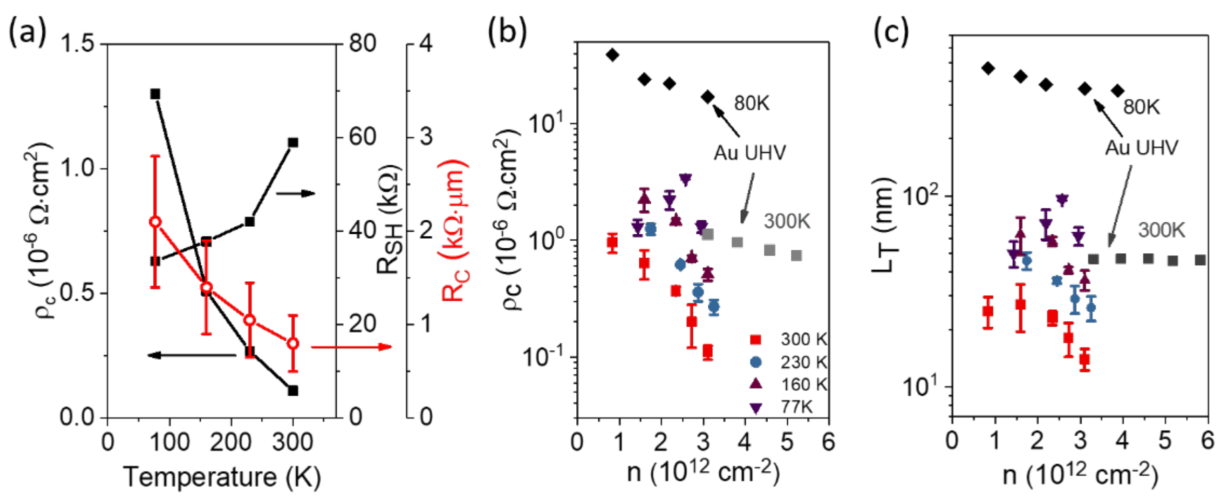


Figure 3: (a) Interfacial resistivity, sheet resistance and contact resistance versus temperature. (b) Interfacial resistivity versus carrier concentration at different temperatures. (c) Transfer length versus carrier concentration at different temperatures. Reported Au contacted $MoS_2$ results are included for comparison.

**Kelvin Probe Force Microscopy**

The soft nature of indium allows it to readily form stable alloys with other metals. This property can be used to adjust the work function of electrodes to facilitate electron or hole injection while maintaining the ultra-clean interface. To demonstrate this, we have deposited ~ 3 nm of In with high work function Pd metal on top. Kelvin force microscopy results shown in Figure 4 shows that the work function of the alloy is slightly increased.

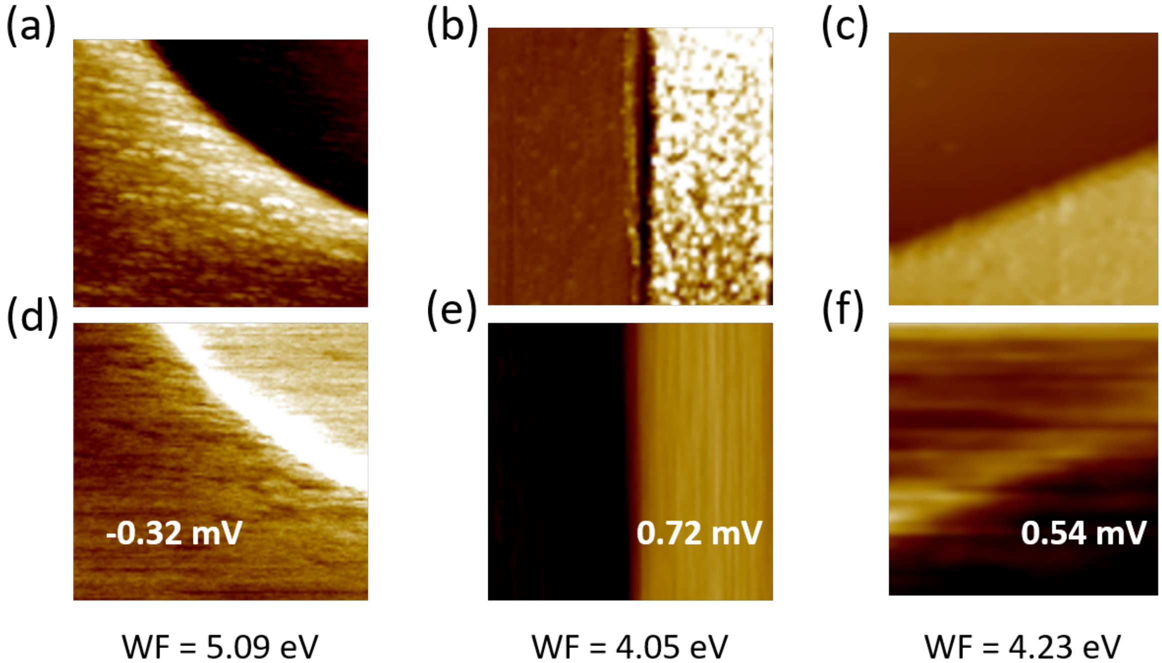


Figure 4 (a) Topographical image of Au sample. (b) Topographical image of In/Au sample. (c) Topographical image of In/Pd sample. (d) Surface potential results of Au sample, the work function (WF) extracted is 5.09 eV, similar to the theoretical value. (e) Surface potential results of In/Au sample, the work function extracted is very close to In work function, 4.05 eV. (f) Surface potential results of In/Pd sample, the work function extracted is 4.23 eV, higher than that of In/Au.

**Ongoing work on p-type contacts**

Our very recent unpublished results suggest it is possible to create clean vdW contacts via direct deposition of high work function metals on single TMD semiconductors (Fig. 5). Our strategy is to use a very low deposition rates and substrate cooling down to 77K to eliminate damage and chemical reactions between the metal and ATB semiconductor. We are in the process of developing a generalized deposition methodology for high work function metals on 2D semiconductors for creation of ultra-clean vdW *p*-type contacts. The metal electrodes on 2D TMDs will then be annealed at 200°C to ensure clean interface and their work functions measured using Kelvin probe force microscopy (KPFM).

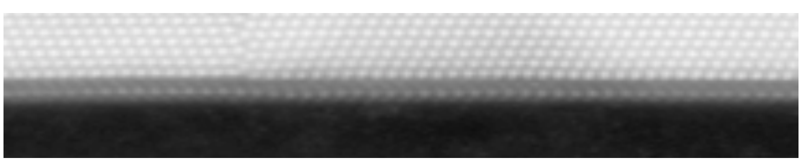

Figure 5: Ultra-clean vdW interface between pure Au and 2D $MoS_2$.

Project Outcomes:

Papers published:

1. Wang, Y. *et al.* Van der Waals contacts between three-dimensional metals and two-dimensional semiconductors. *Nature* **568**, 70 (2019).

Awards:

Yan Wang, the lead PhD student has been selected for the Materials Research Society's Graduate Student Award for the MRS Fall 2019 Meeting.

Personnel Supported by this project:

Yan Wang – completing her PhD at the University of Cambridge
Raymond Fullon – now postdoctoral researcher in the Center for Functional Materials at Brookhaven National Laboratory
Xiuju Song – Now postdoctoral researcher at the University of Manchester in UK

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