Metal Contacts to MoS_2: a Two-Dimensional Semiconductor

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With increasing demands for electrostatic control as scaling continues in today's transistors, low dimensional structures continue to gain attention as a pathway for future device scaling because they offer excellent electrostatic control while remaining compatible with straightforward lithography techniques. In particular, MoS_2 has attracted interest for transistor applications because its large band gap allows for field effect devices with low off-current, unlike graphene [1]. One key bottleneck, however, is the realization of ohmic contacts on MoS_2 to improve FET device on-state performance. With this in mind, we evaluate Ni and Pd contacts on MoS_2 as potential alternatives to the already realized Au-MoS_2 and Ti-MoS_2 contacts [1]. Back-gated transfer length method (TLM) structures with Au, Ni, and Pd contact metals were fabricated on exfoliated MoS_2 flakes, with 300nm SiO_2 on degenerately doped Si as the substrate. The data indicate that Ni, like Au, makes an ohmic contact to the n-doped MoS_2 while the Pd metal contact shows Schottky behavior.

Figure 1 shows the alignment of the metal work-functions to the MoS_2 bands for the high work function metals on which we focus in this work. Figure 2 shows representative I_d-V_{ds} characteristics at V_{bg}=50V for the three contact metals on MoS_2. The MoS_2 flake thicknesses are 5nm for Ni and 6nm for Au, measured by AFM, and ~13nm for Pd, estimated by optical contrast. One finds that the Ni and Au contacts are ohmic while the Pd contact shows Schottky behavior. Figure 3 shows the contact resistance (R_c) as a function of back-gate voltage (V_{bg}), extracted using the TLM. R_c for Ni and Au are found to be comparable, with a minimum R_c of about 4.5Ω.mm at V_{bg}=50V. The gate-dependent R_c reflects the gate modulation of the potential barrier at the metal-MoS_2 interface. Considering charge-transfer at the metal-MoS_2 interface alone for these high work function metals, the different contact nature of Pd from Ni and Au is somewhat unexpected. Indeed, recent *ab inito* calculations suggest that the modification of the electronic states at the interface by the metal is the key to understanding the contact to MoS_2, going beyond the simple charge-transfer considerations of a metal-semiconductor junction [2]. To investigate the Ni contact further, R_c was measured at low temperature via TLM, as shown in Figure 4, for a ~6nm thick flake, as estimated by optical contrast. The R_c varies weakly with temperature, increasing by less than a factor of two from 238K to 78K for any V_{bg}. Enabled by the low temperature Ni ohmic contact, the sheet resistance and mobility of MoS_2 could be extracted as shown in Figure 5. The mobility, extracted from fits to the sheet resistance as a function of V_{bg}, is determined to be 48 cm^2/Vs at 289K, increasing to 237 cm^2/Vs at 78K due to decreased phonon scattering. The mobility of MoS_2 could be significantly improved to several hundred cm^2/Vs if its surface is passivated by atomic-layer-deposited dielectrics. [1, 3] The temperature dependence of the mobility is power law, $\mu \sim T^{-\gamma}$, where γ=1.36 for T=130K and above.

In conclusion, studies of Ni, Au, and Pd metal contacts on MoS_2 reveal that Ni, like Au, is ohmic while Pd shows Schottky contact behavior. Contact resistance for Ni and Au are comparable, with a minimum R_c for both metals of about 4.5Ω.mm at V_{bg}=50V.

References

[1] B. Radisavljevic et al, *Nature Nanotechnology*, **6**, 147 (2011).
[2] I. Popov et al, *Physcial Review Letters*, **108** (2012).
[3] H. Liu and P.D. Ye, *IEEE Electron Device Letters* (in press).

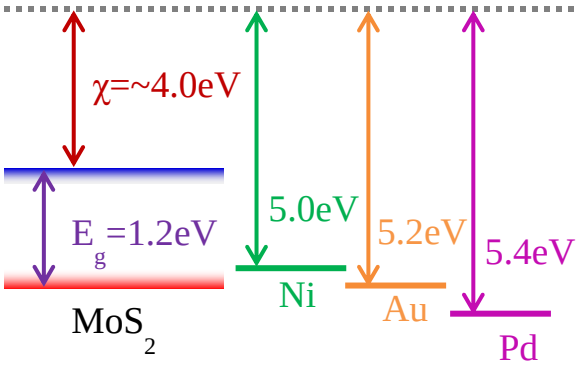

Figure 1: Band diagram showing the work function alignment of the contact metals to MoS_2

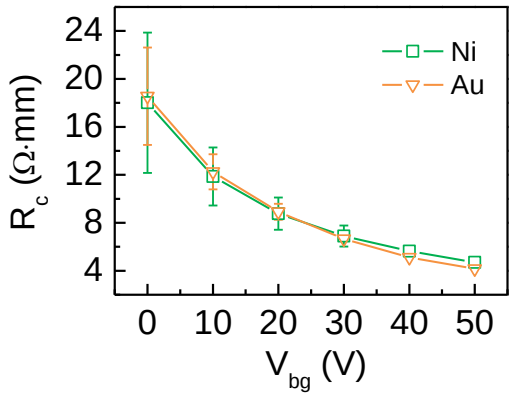

Figure 3: R_c extracted from TLM as a function of gate voltage for Ni and Au contact metals at V_{ds}=50mV. Error bars are determined from the liner fit used to extract R_c. Error bars are omitted for those smaller than the size of the symbol.

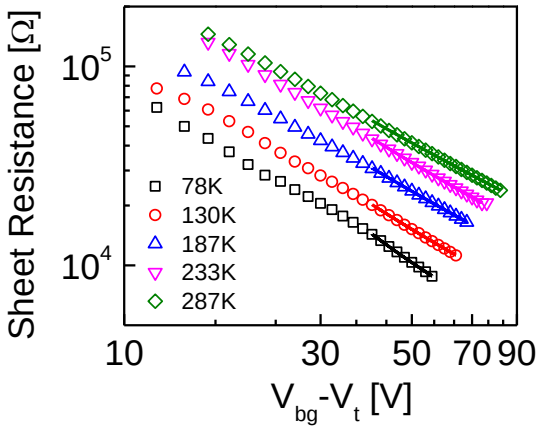

Figure 5: Symbols: Experimental sheet resistance of MoS_2 extracted at V_{ds}=50mV as a function of V_{bg}-V_t for different temperatures for an Ni TLM device. V_t is taken as the V_{bg} where I_d is 10nA. Solid lines: $R_{sheet}=1/C_{ox}(V_{bg}-V_t)\mu$ fits to the data used to extract mobility.

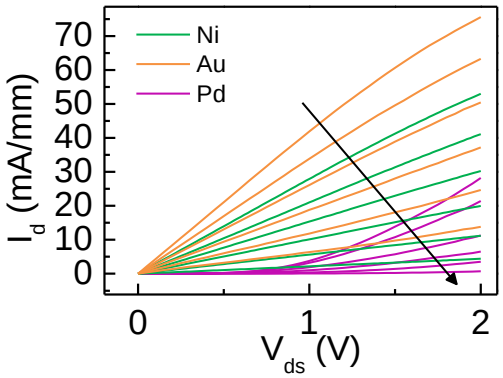

Figure 2: I_d-V_{ds} output characteristics for the three contact metals at V_{bg}=0V to 50V with 10V step. Arrow indicates decreasing V_{bg}. The channel length for all three devices is 500nm.

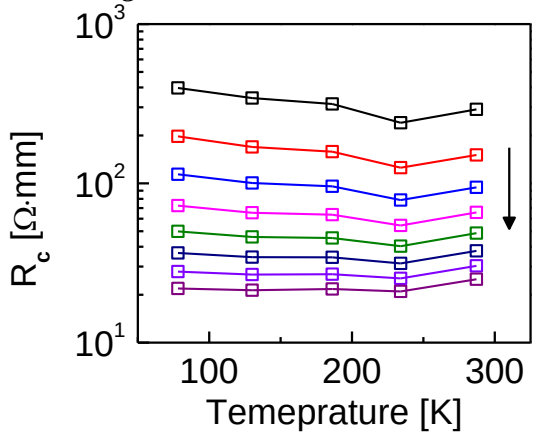

Figure 4: R_c extracted at V_{ds}=50mV as a function of temperature for V_{bg}-V_t from 14V to 56V with 6V step. The sample is different from the one measured in Figure 3. V_t is taken as the V_{bg} where I_d is 10nA. The arrow indicates increasing gate voltage.

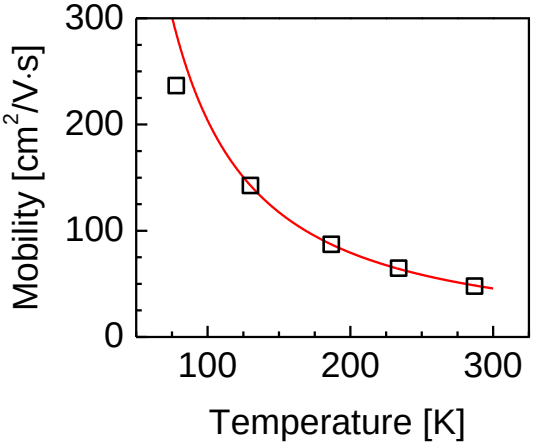

Figure 6: Mobility as a function of temperature extracted from the sheet resistance with power law fit $\mu \sim T^{\gamma}$, where γ=1.36, T=130K and above.