Optimizing Contact Resistance for Improved MoS_2 Device Performance

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Electronics

Abstract:

In recent years, much attention has been directed toward two-dimensional materials given their possible applications in next-generation nanoelectronic devices. Graphene, the most widely studied two-dimensional material, has enjoyed major success due to its attractive electronic, thermal, and optical properties. However, graphene lacks a band gap, which renders it unviable for use as a semiconductor in transistor devices. Like graphene, molybdenum disulfide (MoS_2) is a two-dimensional material with the exception that it has a tunable 1.2-1.9 eV bandgap. As such, transistor devices have been fabricated using MoS_2, but major issues have arisen, including high contact resistance, that have stifled device performance. In this paper, we examine the contact resistances between 7 nm MoS_2 films and various metals — including Au, Ti, Ni, Nb, and Mo — using the two-terminal transmission line method. We also investigate the effect of annealing processes on decreasing contact and sheet resistances.

Introduction:

Semiconducting MoS_2, one of many transition metal dichalcogenides, exhibits strong intralayer covalent bonding combined with weak interlayer van der Waals bonding. MoS_2 has a band gap ranging from approximately 1.9 eV at monolayer thickness to 1.2 eV in bulk, making it ideal for use as a semiconductor in field-effect transistor devices [1]. MoS_2 transistors have displayed large current on/off ratios of ~ 10^8, a subthreshold slope of ~ 60 mV/dec, and a field effect mobility of 10-100 $cm^2 \cdot V^{-1} \cdot s^{-1}$ [2].

However, forming true ohmic contacts to MoS_2 has proven difficult due to a phenomenon known as Fermi-level pinning. Conventionally for semiconductor-metal interfaces, metals are chosen based on their work function alignment with the semiconductor's conduction band or valence band. In contrast, for the MoS_2-metal interface, the Fermi level is partially pinned, resulting in large Schottky barriers for a wide range of metal work functions [2].

Thus, if a metal can be found to not form a large Schottky barrier at the interface, we could significantly enhance device performance.

Experimental Procedure:

Electron-beam evaporation was used to deposit 1-2 nm of Mo on five sapphire substrates. These films were sulfurized in a horizontal tube furnace at 1050°C for 45 minutes. We characterized the films using atomic force microscopy (AFM), Raman spectroscopy, and photoluminescence spectroscopy (PL). AFM indicated a film height of 5-7 nm with 100-200 nm sized grains. A weak PL signal and a Raman peak spacing of ~ 25 wavenumbers also indicated few-layer thick films.

Combined with photolithography, we isolated MoS_2 channels by sulfur hexafluoride (SF_6) plasma etching of the surrounding film. For our contact study, we deposited five metals with a range of work functions: Au, Ti, Ni, Mo, and Nb. These were chosen based on previous reports of low contact resistance using these metals and based on the fact that some of these metals form similar or identical TMD structures with sulfur (i.e., NbS_2 and MoS_2) [3-4].

A finished device is pictured in Figure 1. With the photolithography mask, an array of these devices was fabricated such that the channels varied in length from 0.75 µm to 6.5 µm.

The array of devices allowed for two-terminal transmission line measurements (TLM) to be carried out. Using electrical probes, two-terminal current vs. voltage curves were used to calculate the total resistance of all devices. A linear relationship exists between channel length and total resistance such that the y-intercept, corresponding to zero-length channel resistance, allows for the calculation of the contact resistance while the slope allows for the calculation of sheet resistance through the channel. We computed the contact resistance and sheet resistance values using multiple TLM sets for each metal post-deposition, after a 250°C anneal, and after a subsequent

300°C anneal. All electrical measurements were carried out at room temperature in ambient.

Results and Conclusions:

The results for the effect of the annealing processes on Ni are shown in Figure 2. We concluded that the 250°C anneal was an effective heat treatment as for all the metal contacts there were decreases in contact resistance and/or total resistance. While Ti and Mo contacts saw a slight increase in sheet resistance, other metals showed a decrease in sheet resistance to varying degrees. We also observed that the subsequent 300°C anneal was not an effective heat treatment as it either resulted in little change or an increase in all resistance values.

Figure 3 is a table comparing the sheet resistance and contact resistance for each metal. Ti contacts are inconclusive and unreliable due to a significant scatter in the data (low R^2) and much smaller sheet resistance than all other samples. The data for Au, Ni, Mo, and Nb contacts display true linear trends. However, negative y-intercept values suggest very low contact resistances.

Future Work:

Due to the variation in the data and negative y-intercept values, we plan to repeat TLM measurements in vacuum, after a vacuum anneal, to remove water and other adsorbed species from the MoS_2 surface. We will finish gated devices and perform TLM measurements at different gate biases. Gated TLM measurements are crucial for a fair comparison of devices as there is likely to be variation in the doping levels of the films. That is, we will compare the contact and sheet resistances of all devices at the same bias conditions (i.e., at threshold). We will also use smaller channel lengths as they are more accurate for measuring small contact resistances via TLM method.

Acknowledgements:

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References:

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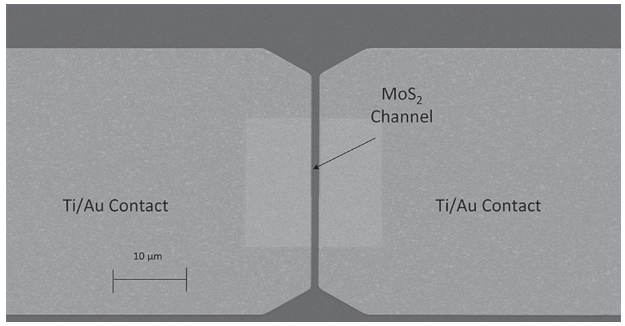

Figure 1: A finished device.

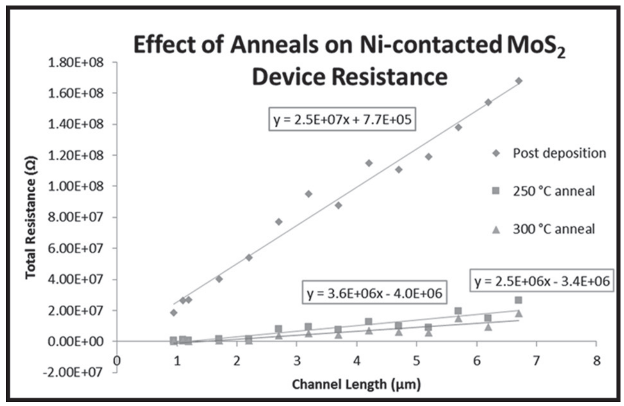

Figure 2: Total Resistance vs. Channel Length for Ni.

Metal	Property	Post-Deposition ($x10^3$)	10 min anneal at 250 °C ($x10^3$)	10 min anneal at 300 °C ($x10^3$)	Coeff. Of determin. (R^2)
Ti	R_C (kΩ·µm)	2.8	2.3	0.11	0.462
	R_S (kΩ/□)	3.3	3.8	2.4	
	R_T (Ω)	550	650	530	
Au	R_C (kΩ·µm)	200	42	78	0.893
	R_S (kΩ/□)	260	60	58	
	R_T (Ω)	5.4E+4	1.4E+4	1.8E+4	
Ni	R_C (kΩ·µm)	9.6	*	*	0.891
	R_S (kΩ/□)	620	37	59	
	R_T (Ω)	7.6E+4	6700	5500	
Mo	R_C (kΩ·µm)	650	190	240	0.898
	R_S (kΩ/□)	2300	2700	1100	
	R_T (Ω)	3.4E+5	3.2E+5	7E+5	
Nb	R_C (kΩ·µm)	*	*	*	0.968
	R_S (kΩ/□)	590	250	580	
	R_T (Ω)	7.3E+4	2.8E+4	6.7E+4	

* - Indicates negative y-intercepts for linear regression fit

All values are averages of multiple TLM arrays

R_c – Contact Resistance
R_s – Sheet Resistance
R_T – Total Resistance for 3.0 µm L_{ch} device

Figure 3: Comparison of sheet and contact resistances for all metals.