# Charge and spin transport in two-dimensional materials and their heterostructures

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# 9 Conclusion


## Abstract

*In this chapter, the outcomes of the research on two-dimensional materials, described in this thesis, are briefly discussed.*

## 9.1 Conclusion

In the past decade, there has been an explosion in the number of electronic gadgets (or e-gadgets) used by us. Also since the last decade, an increasing trend is observed in the down-sizing of these e-gadgets. However, the down-sizing of the e-gadgets is hitting a limit due to the bottleneck in the scaling of the field-effect transistors (FETs) which are the basic units of the e-gadgets. To continue further scaling, as described in chapter 1, there is a need to search for new materials and a need for FETs based on alternative logic. In this quest, the discovery of new two-dimensional materials and a steep development in the research on spintronics [e.g. Spin FET] has emerged as a lifesaver in order for us to continue down-sizing of the e-gadgets, accompanied with improved FET performance (e.g. increased speed and reduced power of operation).

In this thesis, the studies carried out on charge and spin transport measurements on two-dimensional (2D) materials, as part of my PhD research at the University of Groningen (RUG), are reported. The 2D materials studied are germanane, and heterostructures of graphene with transition metal di-chalcogenides (TMDs) like tungsten di-sulfide ($WS_2$) and tungsten di-selenide ($WSe_2$) described in chapter 2. In chapter 3, the basic structural and electronic properties of these 2D materials and their heterostructures are briefly described. Further in chapter 4, the fabrication steps followed in realising the FETs and the spintronics devices (non-local spin valves) of these 2D materials are explained. Additionally, the electrical, magnetic, and optical characterisation techniques performed on these nano-electronic devices are explained in chapter 4.

In chapter 5, the fabrication and optoelectrical characterisation of the first-ever FET of multi-layer germanane realised by us at the RUG is described. Here, the electrical measurement performed on germanane FET showed charge transport in both the electron- and the hole-doped regimes with a high ON-OFF current ratio. Further, optoelectrical measurements showed a significant enhancement of the electrical conductivity in germanane FET under illumination with a red laser. Our observation of both the ambipolar charge transport and the optoelectronic response in germanane FET promises great potential in complementary metal oxide semiconductor (CMOS) and (opto)electronic applications.

One of my added areas of interest, other than studying FETs of 2D materials, was studying spintronics in 2D materials; wherein I wanted to study the electron spin transport in graphene. In line with this, the fabrication and the characterisation of spin valves on a heterostructure of the graphene with multilayer $WSe_2$ ($WSe_2$ covered the graphene partly) is reported in chapter 6. The objective was to study and compare the spin transport in graphene which is covered and not-covered by $WSe_2$. The main observations are:

1. The absence of the in-plane spin transport across the $WSe_2$ covered graphene, when the $WSe_2$ coverage was longer than 3 μm, which alludes to a large magnitude of the induced spin-orbit coupling (SOC) by the $WSe_2$ in graphene.
2. The presence of spin lifetime anisotropy for in-plane ($\tau_{\parallel}$) and out-of-plane ($\tau_{\perp}$) spin transport with their ratio being $\tau_{\perp}/\tau_{\parallel} = 3.5$; which is due to the anisotropic SOC induced by the $WSe_2$ in graphene. Surprisingly, the difference in spin lifetimes as a

result of the proximity induced SOC could also be non-locally determined in the nearby region of graphene not covered by $WSe_2$; this is due to the diffusing nature of the itinerant spins which explore the neighbouring $WSe_2$ covered graphene region.

3. Use of multi-layer $WSe_2$ as an intermediate layer for spin injection into graphene to study the use of TMDs as a tunnel barrier for spin injection into graphene.
4. The Hanle curves obtained from the modeled spin transport under and near the $WSe_2$ covered graphene regions shows an agreement between the simulation and experimental observations of the anisotropic behaviour in graphene near the $WSe_2$ covered graphene region.

Promising theoretical predictions of spin transport properties in bi-layer graphene (BLG), in the proximity of TMD, motivated us to study the same experimentally. Hence, in chapter 7, the spin transport in BLG which is spin-orbit coupled to a multi-layer $WS_2$ substrate is studied. We were able to measure a record spin lifetime anisotropy of ~40-70, i.e. the ratio between the $\tau_\perp$ and $\tau_\parallel$. Also in chapter 7, we developed a new tool called the Oblique spin-valve measurement to calculate this anisotropic ratio by exploiting the shape-anisotropy of the ferromagnetic electrodes. Our observation of high $\tau_\perp$ and high spin lifetime anisotropy are clear signatures of strong spin-valley coupling for the out-of-plane spins in BLG/$WS_2$ systems in the presence of SOC; this unlocks the potential of BLG/TMD heterostructures for developing future spintronic applications.

Further, the spin transport in BLG/TMD heterostructure was also explored with another TMD, i.e. $WSe_2$ in device geometry similar to that presented in chapter 6. In chapter 8, the spin transport studies on BLG with $WSe_2$ heterostructure is described. Our observations are similar to that reported in chapter 6 and 7, these include:

1. No in-plane spin transport is observed across the $WSe_2$ covered BLG, although we could measure an out-of-plane spin transport, signifying a strong anisotropy in $\tau_\parallel$ and $\tau_\perp$.
2. The spin lifetime anisotropy in $WSe_2$ covered BLG was found to be $\tau_\perp/\tau_\parallel = 3.64$ (which is due to the anisotropic SOC induced by $WSe_2$ in BLG). We also measured the spin lifetime anisotropy in in BLG near the $WSe_2$ covered BLG; this is due to the diffusing nature of the itinerant spins, and these diffusing spins could explore the neighbouring $WSe_2$ covered BLG region.

Additionally in chapter 8, the FETs of $WSe_2$/BLG in vertical geometry, which showed an n-type behaviour with a current ON-OFF ratio $>10^3$, are discussed.

The study of charge and spin transport in 2D materials, discussed in this thesis, is a step up in our understanding of these new generations of nano-electronic devices for their applications in the technology of the future.