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2D materials and interfaces in high-carrier density regime

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DOI:
10.33612/diss.94903687

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Ali El Yumin, A. (2019). *2D materials and interfaces in high-carrier density regime: a study on optoelectronics and superconductivity*. University of Groningen. https://doi.org/10.33612/diss.94903687

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Download date: 16-05-2021

SUMMARY

Semiconductor technology becomes an essential part of modern life. Starting from the emergence of quantum mechanics theory and, then, the invention of the transistor, almost every aspect of modern society relies on semiconductor devices. The use of semiconductor is so universal that applications ranging from energy harvesting to powerful supercomputers can be realized. Especially, in optoelectronics, various discovery and developments of new materials have been accomplished to obtain efficient and scalable devices for the next generation technologies. For that reason, the study of semiconductor is continuously progressing to understand the nature of newly discovered materials.

2D materials are major examples that have been extensively studied in the last decade. The invention of graphene in 2004 has been a major breakthrough in material science. The exceptional electronic mobility and atomic scale thickness became the main interest of this material. However, the absence of electronic bandgap becomes a crucial disadvantage for graphene to substitute present silicon-dominated semiconductor technology. Therefore, it stimulates the exploration of new-layered materials beyond graphene to provide a diversity of building blocks to realize low-dimensional device technology based on 2D materials.

Transition metal dichalcogenides (TMDs) group are the most promising candidate to replace the present semiconductor technology. Their layered nature, analog to graphene, and the existence of finite electronic band gap in particular compounds such as WS_2, WSe_2, MoS_2, and MoS_2 have been a major interest of these 2D materials group. Not to mention, the superconducting (SC) TMDs have been discovered in $NbSe_2$ and TaS_2, which give more variety in 2D materials building blocks. Furthermore, with the development of the 2D heterostructure fabrication method, the wide application of 2D materials devices starts to be investigated.

This thesis focuses on the studies of optoelectronic properties and electronic transport in the interface of two different electronic states of 2D TMDs. In this thesis, two general ideas are implemented: *p*- and *n*-type semiconductor interface, namely *p*-*n* junction, and superconducting-normal metal interface. The realization of the ideas is related to the incorporation of electrical double layer transistors (EDLTs) configuration in which the high carrier density regime (n_{2D} ~

10^{14} cm^{-2}) can be easily accessed. Chapters 2 and 3 discuss the development of lateral 2D *p-n* junction based on TMDs-BN artificial heterostructure in which the lateral *p-n* interface is tuned using the combination of EDLT and conventional solid-state gating. Chapter 4 focuses on electrical transport in the superconducting-normal metal junction of field-induced few-layer MoS_2 superconductor. Chapter 5 demonstrates the development of a novel technique in 2D heterostructure fabrication technology to achieve high-quality 2D heterostructure devices.

In **chapter 2**, we demonstrated the development of lateral 2D *p-n* junction based on TMDs-BN artificial heterostructure. We developed a lateral 2D *p-n* diode and investigated the electrical performance of the devices by tuning the electrostatic gating. We incorporate the EDLTs configuration to access high carrier density regime and tune the intrinsic *n*-type TMDs into *p*-type. Our observation showed that the electrical performance is thickness dependent and observed the stable *p-n* junction behavior on the thinner layers with the highest rectification ratio of 33000. In thicker layers, the device performance was strongly influenced by unintended conductive bottom layer, which facilitated additional channel for reverse-bias current. Furthermore, strong and well-defined electroluminescence (EL) was observed in the monolayer device.

The use of thinner layer TMDs is necessary in order to give better 2D diode electrical performance. In **chapter 3**, we incorporated monolayer TMDs to achieve ultimate device performance since the electronic transport was expected to be confined in a two-dimensional system. We demonstrated the fabrication of a 2D lateral *p-n* junction based on CVD grown monolayer WS_2 and implemented the device architecture described in the previous chapter to obtain a sharp and well-defined *p-n* interface. The confocal microscopy images of the electroluminescence (EL) confirmed that the lateral 2D *p-n* interface is sharp and stable. Moreover, we investigated the electronic performance of the device, which showed efficient gate tunability due to a combination of ionic liquid and high-*k* dielectric gate. Furthermore, we investigated optoelectronic performance and the correlation with induced carrier density. We observed that the exciton species rate from the EL spectra strongly depends on induced carrier density ratio between the *p*- and *n*-type side of the *p-n* junction.

The electronic transport measurement of the superconducting-normal metal interface in field-induced superconducting MoS_2 became a focus discussion of **chapter 4**. Using the EDLT method, the superconducting state of MoS_2 can be accessed by inducing high carrier density (n_{2D} ~ 10^{14} cm^{-2}). In order to characterize the SC gap on the confined SC state, we measured the tunneling spectrum in normal-insulating-SC (N-I-S) junction and observed the quasi-particle peaks as a signature of the Andreev reflection. Our experimental results can be well described with the Blonder-Tinkham-Klapwijk (BTK) theory yielding the magnitude of the SC gap. Furthermore, our study showed the modulation of the SC gap in the range of Δ = 0.8 to 1.12 meV as a function of carrier density by tuning the back-gate voltage. In addition, we studied the electron-phonon coupling interaction in different carrier densities indicating the coupling enhancement in the medium coupling range ($\lambda_{e\text{-}ph}$ = 0.6 - 0.9) as the n_{2D} increased.

Finally, in **chapter 5**, we demonstrated the development of the new 2D heterostructure fabrication technology, which is performed inside a high-vacuum environment (~ 10^{-6} mbar) to realize high-quality heterostructure devices. We described the detailed technical process of making 2D heterostructure in vacuum followed by an evaluation of sample quality by AFM and optical spectroscopy. The fabricated sample showed clean and flat surface quality as the extracted average value of surface roughness was ~135 pm. Furthermore, we observed sharp biexciton emission with a linewidth of 4.9 meV at low-temperature photoluminescence (PL) spectroscopy (T = 5 K) confirming the high-quality sample. With high demand and rapid development of 2D materials technology, we believe that our attempt to develop new fabrication technology will be a significant contribution in 2D optoelectronics applications.