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

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Acknowledgement

As the saying goes, everything that has a beginning has an end, and I'm glad that my PhD journey comes to a glorious end this autumn. During the course of this journey, which was filled with ups and downs, many have directly or indirectly supported me on both professional and personal level, and I would like to take this opportunity to thank them for their support here.

During my Master's research on studying charge and spin transport in two-dimensional (2D) materials, I was intrigued by the fabrication, characterisation and physics of the nanodevices made out of 2D materials. This fascination with 2D nanodevices propelled me to look for a PhD position to work with and understand them at a deeper level. In this direction, the Physics of Nanodevices (FND) group spearheaded by Prof. B.J. van Wees was one of my top priorities on my scout for a PhD position, sheerly because of the excellence amassed by the group in the study of charge and spin transport in graphene, to the extent of being the go-to place in the world. After a visit to the group with a walking tour of the lab and interacting with Prof. Bart, I was offered a PhD position in the group. I wholeheartedly accepted the position and was excited to start my PhD journey at the University of Groningen in the Netherlands.

Being overseen by Prof. Bart on my PhD journey, I can outline his role as a supervisor as accessible, supportive, critical, scientific acumen and eye for detail. To elaborate, his office door was always open for me to drop by for any scientific discussion, which is crucial when I worked with nanodevices which are sometimes wacky so to speak. He gave me the freedom to choose the research topic I wanted to pursue; at the same time, he never fell short of giving me his critical feedback through a scientific lens. His eye for detail while sifting through the scientific data and graphs kept me on my toes. On a final note, it has been a great learning experience for me to work with you Prof. Bart and I would like to thank you wholeheartedly for your part in my PhD journey.

It was my pleasure to have Prof. C.H. van der Wal as my co-supervisor. I would like to thank you for providing me with access to optical tools and your insights during the optical characterization of germanane field-effect transistors. Your constructive feedback during the routine R&O interviews helped me steer the course of my PhD. Thank you also for offering me to tutor the Quantum Physics course which was a great teaching experience for me.

I would like to thank Prof. S.P. Dash, Prof. M.A. Stöhr and Prof. J. Ye for accepting to be on the assessment committee and taking their invaluable time to review my PhD thesis. I very much appreciate the feedback provided during the review process. I would also like to thank the committee members for being considerate when the defence dates were moved due to the pandemic.

Alexey, I thoroughly enjoyed collaborating with you on realising and understanding the germanane field-effect transistors, which is covered in chapter 5 of this thesis. I always felt at ease to ask you questions and moreover, I appreciate you taking the time to answer my questions and explain the concepts in detail. I was also bemused and influenced by your ritualistic athletic lifestyle, keep it up!

In line with the research work presented in chapter 5 of this thesis on germanane field-effect transistors, I would like to thank all the collaborators. Theodosios and Prof. Dimitrios, thank you for synthesising and shipping the germanane to Groningen all the way from Ioannina, Georgia. Prof. Graeme and Prof. Petra, thank you for performing the material analysis of germanane.

Jorge, thanks for the modelling of spin transport in graphene in proximity to WSe₂ presented in chapter 6 of this thesis. I appreciate your analytical and critical questioning in scientific discussions, be it with me or in the team meetings.

Mallik, your actions speak louder than words be it in your academic or personal life. You never fell short of patiently explaining the scientific jargons as well as teaching the tip and tricks of exfoliation and stacking of 2D materials. I thoroughly enjoyed our table talk in the afternoons, which also helped wean my mind off work! Locking you up in a cupboard, taking pictures of your headstands, eating out at De Pastafabriek are some of the memories out of many that I will always cherish. I always wish the best for you and I hope we catch up with each other more often than we do now. Sid, you were my comrade-in-arms during my PhD journey. It was my absolute pleasure to work with you on the research topics presented in chapter 6, 7 and 8 of this thesis. I appreciate that you tried your best to explain and answer the umpteen number of questions I had in spintronics. My kudos to your scientific acumen, work ethics and cooking skills. I very much appreciate your guidance all along my PhD journey. I'm also glad that you moved to Eindhoven and that we both work in the same company. I am looking forward to checking off every item on the south-Indian menu of Krishna Vilas and exploring Eindhoven with you. Mallik and Sid, you both hold a special place in my heart. And so, you both were an obvious choice to be my paranymphs! Thank you both for accepting the honour.

Herman, I relish the time I spent supervising your bachelor's research project. Your enthusiasm and humbleness to learn with a big smile on your face is something I will remember for a very long time. One more thing, fabricating an almost perfect stack of 2D material after just a month or two of training is a feat in itself! Jeroen and Talieh, it was my pleasure supervising your master's research project. Jeroen, I especially admire your calm personality, your scientific acumen and the nice complete thesis you produced. And, Talieh, it was good to see you join the group as a fellow colleague. I wish you both much success in your further career.

Having worked in a couple of research labs before the start of my PhD, I can definitely say that one was required to solder the wires, fix the pump, order a piece of equipment, etc. Although these tasks could teach you the nitty-gritty of How to run a lab? they could take significant time off of your PhD research. In this context, I was very fortunate to have a solid combined technical assistance provided by Johan, Anna, Tom, Martijn, Herman and Hans. Thank you all for your help!

Johan, I always enjoyed our informal conversation in your office and it was very comforting whenever you checked on my personal well-being. Tom, I had the pleasure to share the office space with you. Having a personal interest in design software, I was always intrigued by the different software you used to design things for the lab. And, when I had a question, you

would enthusiastically answer and even demonstrate the model you were building on the software. I very well remember the smile on your face on the day when you had your granddaughter, Aurora. One day, I want to visit your windmill! And I hope that day is soon. Martijn, I appreciate your help with procuring the Helium, wire bonding my samples and dropping by quickly when I had an issue with any instrument in the lab. Outside work, I enjoyed our conversation during occasions like borrel, group outing, etc. I wish you the best with your career in Norway. Herman, your first-hand knowledge of electronics was evident when you helped me demystify the electronic components that went into the switch box. At the same time, I could recognise and appreciate the reasoning and effort you put into designing some of the switch boxes yourself. Hans, I have to say that your smile is quite contagious! You put a smile on my face whenever I ran into you and I always enjoyed chatting with you. Johan Kuiper, thanks for arranging the Helium used for my experiments, sometimes even on short notice! Anna, I appreciate your work ethics, particularly your clear and swift response to my queries or help needed. I'm thankful for the time you helped me deal with the bureaucracy of an unfortunate bike accident.

Having spent a long time with the scientific instruments in the lab, I have certainly developed a personal connection with each one of them, to the extent of recognising that each has its own personality! I would like to acknowledge their significant role in the outcome of my PhD research.

Prof. Tamalika, I always felt at home when I spoke with you. I appreciate that you took the time to know me and care for me. I will miss your periodic inventory of Indian sweets and the countless birthday dinners.

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At FND, I had the pleasure of working in a multicultural environment with colleagues who came from all over the world with different academic training. I thoroughly enjoyed working and learning from each of them.

Arijit, I still can't wrap my head around finding you in the lab even in the evenings and weekends! I wish all your hard work takes you to your destiny. Arjan, you always had your way to crack me up in our casual talks and I wish you keep it up! Christian, seeing the progress with your experiments in our team meetings was a great learning experience for me. I also applaud your instrumentation skills.

Crystal, your smile and personality have the ability to cheer others up. I always enjoyed dropping by your office to have a quick chat. Geert, it was always great discussing with you over our mutual experimental difficulties and your sailing knowledge. I hope to sail with you someday! Please invite me next time.

Prof. Ivan, it was always my pleasure to meet you in conferences or when I peeked into the

skype calls of Kumar and Sid. Thanks for the scientific discussions and the questions you had on my research topic.

Jing, thanks for greeting me with a smile every time I passed by your office. I will strive to travel and eat as healthy as you. Juan, it was my pleasure to have known you and your husband Lei. You were always pleasant to talk to. As we work in the same company now, I appreciate you catching up with me when I joined newly. I hope our paths cross more often. Kumar, you certainly raised the bar to dress up to work in FND. I was always glad to drop by your office to ask for help and you always obliged with a smile.

Prof. Marcos, I enjoyed our occasional science talks as you joined RUG only when I was finishing my research work. Congratulations and wish you the best!

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Pep, I appreciate your ability to cite the papers right off the bat which exposed me to new topics. Ping, it was always sweet talking with you and learning about your research and china. Tom, it was always nice to catch up with you in the hallway or when I wanted to borrow or lend Helium! Xu, thanks for organising all the social events at FND. It was nice learning about your cool experiments in our team meetings.

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Apoorva, thank you for tolerating me! Your practical approach to life gave me the lens to push through my PhD journey towards success. To-date, I thoroughly enjoy our discussion on anything science and I have always envied your style quotient. I love you and I'm looking forward to our journey of forever.

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heterostructure presented in this thesis. I have enjoyed playing online games with you, our tech talks and our short euro trip helping me ease my mind off PhD.

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Mexican food! I wish to visit you both in Aguascalientes City and meet both your lovely kids.

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Thank you,

Madhushankar (Madhu) Bettadahalli Nandishaiah
Eindhoven, Netherlands
27th September, 2020

Publication list

1. “Electronic properties of germanane field-effect transistors”
B.N. Madhushankar, A. Kaverzin, T. Giouis, G. Potsi, D. Gournis, P. Rudolf, G.R. Blake, C.H. van der Wal, B.J. van Wees,
2D Materials 4 (2), 021009 (2017).
2. “Large spin-relaxation anisotropy in bilayer-graphene/WS₂ heterostructures”,
S. Omar, B.N. Madhushankar, B.J. van Wees
Physical Review B 100 (15), 155415 (2019).
3. “Study of proximity-induced SOC and anisotropic spin relaxation in single layer graphene – multi-layer WSe₂ van der Waals heterostructures”
B.N. Madhushankar, S. Omar, J. Quereda, B.J. van Wees
Manuscript in preparation.
4. “Study of proximity induced SOC in WSe₂/bilayer graphene heterostructures”
B.N. Madhushankar, S. Omar, B.J. van Wees
Manuscript in preparation.
5. “Low Schottky Barrier Black Phosphorus Field-Effect Devices with Ferromagnetic Tunnel Contacts”,
M.V. Kamalakar, B.N. Madhushankar, A. Dankert, S.P. Dash
Small 11 (18), 2209-2216 (2015).
6. “Effect of high-k dielectric and ionic liquid gate on nanolayer black-phosphorus field effect transistors”,
M.V. Kamalakar, B.N. Madhushankar, A. Dankert, S.P. Dash
Applied Physics Letters 107 (11), 113103 (2015).
7. “Water-Gated Phospholipid-Monolayer Organic Field Effect Transistor Through Modified Mueller-Montal Method”,
K.S. Narayan, B.N. Madhushankar, V. Gautam, S.P. Senanayak, R. Shivanna
IEEE electron device letters 34 (2), 310-312 (2013)

Resume

Madhushankar Bettadahalli Nandishaiah

9 June 1989 Born in Bengaluru, India

Education

2015-2020 **PhD in Physics**

University of Groningen, Groningen, Netherlands

Dissertation in the group of Prof. B. J. van Wees

“Charge and spin transport in two-dimensional materials and their heterostructures”

2012-2014 **Erasmus Mundus Master of Science in Nanoscience and Nanotechnology**

KU Leuven, Leuven, Belgium and Chalmers University of Technology, Gothenburg, Sweden

Thesis in the group of Prof. S. P. Dash; daily supervised by Dr. A. Dankert and Dr. M. V. Kamalakar

“Field Effect Transistors of Two-Dimensional Semiconducting Crystals”

2007-2011 **Bachelor of Engineering in Telecommunication Engineering**

Ramaiah Institute of Technology, Bengaluru, India

Thesis supervised by Prof. Premila Manohar and Prof. Shobha K. R.

“Auto-parachute deploy unit with GPS tracking”

Work Experience

2020-Present **Design Engineer**

ASML, Veldhoven, Netherlands

2019-2020 **Application Engineer**

ASML, Veldhoven, Netherlands

2013 **Graduate Intern**

IMEC, Leuven, Belgium

Research supervised by Prof. Andre Stesmans and Dr. J. Mitard

“Study on the thermal passivation of the Ge interface by deuterium in Ge/oxide based devices”

2011-2012 **Research and Development Assistant**

JNCASR, Bengaluru, India

Research performed in the group of Prof. K. S. Narayan and daily supervised by Dr. S. P. Senanayak

“Fabrication and opto-electronic characterization of thin-film organic FET”

2010 **Summer Fellow**

IIT-Madras, Chennai, India

Study performed in the group of Prof. Mahesh Kumar and daily supervised by Dr. S. B. Karanki

“Study of protocols, compression technology and file analysis procedures for G4500 Black Box”