UNIVERSITY OF TECHNOLOGY SYDNEY
Faculty of Mathematical and Physical Sciences

Applied Nanophotonics with Two-Dimensional Materials

by

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A Thesis Submitted
in Partial Fulfillment of the
Requirements for the Degree

Doctor of Philosophy

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Sydney, Australia

July 2020

Certificate of Authorship/Originality

I certify that the work in this thesis has not been previously submitted for a degree nor has it been submitted as a part of the requirements for other degree except as fully acknowledged within the text.

I also certify that this thesis has been written by me. Any help that I have received in my research and in the preparation of the thesis itself has been fully acknowledged. In addition, I certify that all information sources and literature used are quoted in the thesis.

This research is supported by an Australian Government Research Training Program Scholarship

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Date: 07 July 2020

ABSTRACT

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Silicon semiconductor technology has revolutionized electronics beyond the imagination of pioneering scientists. This technology's rate of progress since 1947 has been enormous, with the number of transistors on a single chip growing from a few thousand in the earliest transistors to more than two billion today. However, there seems to be a limit to the miniaturization of electronics chips, when the size of individual transistors can no longer be reduced, or they become unstable when quantum tunneling starts to kick in at a few atoms limit. Therefore, there is an urgent need to complement Si CMOS technology and to fulfil future computing requirements as well as the need for diversification of applications with new materials. In that context, two-dimensional (2D) materials emerge as a promising alternative. They demonstrate a range of superior optical and electronic properties, which are essential for future optoelectronic applications. In the crystal form, thin layers of these materials are stacked and held together by relatively weak van der Waals forces. Consequently, it is easier to exfoliate and transfer them to a target substrate by a simple tape exfoliation and stamping method. This is a substantial advantage of 2D materials over their three-dimensional (3D) counterparts for incorporation in devices.

2D materials promise a heterogeneous platform that is particularly appealing for on-chip integration, owing to their small footprints and compatibility with semiconductor technology. In this thesis, we investigate the engineering of hexagonal boron nitride (hBN) at the nanoscale to generate single photon emitters in hBN flakes and nanoparticles. Next, we discuss the effort to develop novel nanophotonic platforms by integrating hBN quantum emitters in dielectric waveguides; we successfully coupled and propagated quantum light in hBN through the waveguides. Finally, we present the work on the incorporation of transition metal dichalcogenide (TMDC) material in a circular Bragg's grating structure to improve the directionality of the emitted photon stream and light extraction efficiency.

Dissertation directed by Professor Milos Toth, Professor Igor Aharonovich
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Dedication

To my loved ones

Acknowledgements

I would like to thank my supervisors Professor Milos Toth and Professor Igor Aharonovich, who have sparked my interest in nano-science and offered me the opportunity to explore the exciting field of nanophotonics. I am grateful to have their guidance and for the freedom in research that I immensely enjoyed. It is because of their endless support, understanding, and patience that I can advance in my research. The experience that I have obtained by working in their group will be of priceless importance for my future career.

I would like to acknowledge the collaborators, and constructive comments I have received from Professor James Edgar, Professor Alexandra Radenovic, Professor Shigeki Takeuchi, and Professor Takeshi Ohshima for the projects in my thesis.

I would like to express my gratitude to academic staffs – Dr. Toan Trong Tran, Dr. Mehran Kianinia, Dr. Alexander Solntsev, Dr. Sejeong Kim, Dr. Zai-quan Xu, Dr. James Bishop, and Dr. Carlo Bradac – who get involved in my research, help me with experiment designs and share their invaluable experience. Without their mentorship, I could not have been able to finish the projects promptly.

Special thanks are due to the technical staff of the Microstructure Analysis Unit (MAU) – Mr. Geoff McCredie, Ms. Katie McBean, Mr. Mark Berkahnand and Mr. Herbert Yuan. They have been providing me induction to the laboratory facility. They are also maintaining, troubleshooting, and upgrading to keep the facilities at their top performances so that I can finish my experiments.

Throughout my education, I was fortunate to have excellent fellow students who have helped me through technical problems and given me useful advice. It has been a great pleasure to know you and work with you guys - Minh Nguyen, Johannes Froech, Alexandra Trycz, Chi Li, Blake Reagan, Tung Huynh, Anh Ly, Thinh Tran, Noah Mendelson and Connor Stewart.

I would like to extend my gratitude towards the Research Training Program (RTP) scheme from the Department of Education and Training for funding my stipend.

Finally, I am grateful for the constant love and support that I have been receiving from my brother Nhut Minh, my parents Nhut Long and Ngoc Thuy and my family in Vietnam. My parents have developed my interest in science and technology. They are my greatest inspiration and my first teachers. Especially, I am grateful for love, devotion and support from my beloved husband Tien Thong, who has always put up with me and be by my side through difficult times and helped me reach my dream. This thesis is for them.

Ngoc My Hanh Duong

Sydney, Australia, 2020.

List of Publications

Journal Papers

Articles with results included in this thesis

J-1. **NGOC MY DUONG, H.**, NGUYEN, M. A. P., KIANINIA, M., OHSHIMA, T., ABE, H., WATANABE, K., TANIGUCHI, T., EDGAR, J. H., AHARONOVICH, I. & TOTH, M. 2018. Effects of High-Energy Electron Irradiation on Quantum Emitters in Hexagonal Boron Nitride. *ACS Applied Materials & Interfaces*, 10, 24886-24891.

J-2. **NGOC MY DUONG, H.**, XU, Z.-Q., KIANINIA, M., SU, R., LIU, Z., KIM, S., BRADAC, C., TRAN, T. T., WAN, Y., LI, L.-J., SOLNTSEV, A., LIU, J. & AHARONOVICH, I. 2018. Enhanced Emission from WSe2 Monolayers Coupled to Circular Bragg Gratings. *ACS Photonics*, 5, 3950-3955.

J-3. KIM, S., **NGOC MY DUONG, H.**, NGUYEN, M., LU, T.-J., KIANINIA, M., MENDELSON, N., SOLNTSEV, A., BRADAC, C., ENGLUND, D. R. & AHARONOVICH, I. 2019. Integrated on Chip Platform with Quantum Emitters in Layered Materials. *Advanced Optical Materials*, 7, 1901132.

J-4. **NGOC MY DUONG, H.**, GLUSHKOV, E., CHERNEV, A., NAVIKAS, V., COMTET, J., NGUYEN, M. A. P., TOTH, M., RADENOVIC, A., TRAN, T. T. & AHARONOVICH, I. 2019. Facile Production of Hexagonal Boron Nitride Nanoparticles by Cryogenic Exfoliation. *Nano Letters*, 19, 5417-5422.

Articles with results not included in this thesis

J-5. **NGOC MY DUONG, H.**, REGAN, B., TOTH, M., AHARONOVICH, I. & DAWES, J. 2019b. A Random Laser Based on Hybrid Fluorescent Dye and

Diamond Nanoneedles. *physica status solidi (RRL) – Rapid Research Letters*, 13, 1800513.

J-6. BISHOP, J., FRONZI, M., ELBADAWI, C., NIKAM, V., PRITCHARD, J., FRÖCH, J. E., **NGOC MY DUONG, H.**, FORD, M. J., AHARONOVICH, I., LOBO, C. J. & TOTH, M. 2018. Deterministic Nanopatterning of Diamond Using Electron Beams. *ACS Nano*, 12, 2873-2882.

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Abbreviation

2D: Two-Dimensional

3D: Three-Dimensional

TMDCs - Transition Metal Dichalcgenides

hBN - Hexagonal Boron Nitride

WSe_2 - Tungsten Diselenide

PL - Photoluminescence

RWA: Rotating Wave Approximation

SPE: Single Photon Emitter

CVD: Chemical Vapour Deposition

PMMA - Polymethyl Metacrylate

CW - Continuous Wave

AFM - Atomic Force Microscopy

ZPL - Zero Phonon Line

FWHM - Full Width at Half Maximum

PDMS - Polydimethylsiloxane

QD - Quantum Dot

FDTD - Finite-Difference Time-Domain

NA - Numerical Aperture

PSB - Phonon SideBand

AlN - Aluminum Nitride

FFT - Fast Fourier Transform

HBT - Hanbury Brown and Twiss

EMCCD - Electron Multipying CCD

SMLM - Single Molecules Localization Microscopy

CBG - Circular Bragg Grating

Si_3N_4 - Circular Bragg Grating

SEM - Scanning Electron Microscopy

CL - Cathodoluminescence

Nomenclature and Notation

Capital letters denote matrices.

Lower-case alphabets denote column vectors.

k denotes modulus of the wave vector.

E is the electric field.

h is the Planck constant $n \times n$.

v denote the photon velocity.

$\vec{\epsilon}$ defines the direction of the electric field.

V is the quantization volume.

$\hbar\omega_0$ is the energy difference between the two levels.

F_P denote the Purcell factor.

Q is the quality factor.

V_0 is the mode volume.

I(σ^+) and I(σ^-) are right and left circularly polarized emission, respectively.

ρ denote the degree of PL polarization.