

UNIVERSITY OF TECHNOLOGY SYDNEY
Faculty of Mathematical and Physical Sciences

**Applied Nanophotonics with Two-Dimensional
Materials**

by

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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.

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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
School of Mathematical and Physical Sciences

Dedication

To my loved ones

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List of Publications

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- 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.
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Abbreviation

2D: Two-Dimensional

3D: Three-Dimensional

TMDCs - Transition Metal Dichalcogenides

hBN - Hexagonal Boron Nitride

WSe₂ - 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 Multiplying 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.

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

v denote the photon velocity.

\vec{e} 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.

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

ρ denote the degree of PL polarization.