

**BOTTOM-UP  
FABRICATION OF  
SINGLE PHOTON  
EMITTERS IN  
HEXAGONAL BORON  
NITRIDE**

**By**

**Noah Mendelson**

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# Certificate of Authorship

I, Noah Mendelson declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the department of Mathematical and Physical Sciences at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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Date:            June 21<sup>th</sup>, 2021

**This work is dedicated to my Mom & Pop.**

**And to Benny Nelson.**

**To all my friends and loved ones.**

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# List of Publications During PhD

## **First Author Publications**

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Note \* Indicates Equal Authorship

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2. **Noah Mendelson**, Marcus Doherty, Milos Toth, Igor Aharonovich, Toan Trong Tran. Strain-Induced Modification of the Optical Characteristics of Quantum Emitters in Hexagonal Boron Nitride. *Advanced Materials*, **2020**, 32, (21), 1908316.
3. **Noah Mendelson**, Zai-Quan Xu, Toan Trong Tran, Mehran Kianinia, John Scott, Carlo Bradac, Igor Aharonovich, Milos Toth. Engineering and tuning of quantum emitters in few-layer hexagonal boron nitride. *ACS Nano*, **2019**, 13, (3), 3132.
4. **Noah Mendelson**, Luis Morales-Inostroza, Chi Li, Ritika Ritika, Minh Anh Phan Nguyen, Jacqueline Loyola-Echeverria, Sejeong Kim, Stephan Götzinger, Milos Toth, Igor Aharonovich. Grain Dependent Growth of Bright Quantum Emitters in Hexagonal Boron Nitride. *Advanced Optical Materials*, **2020**.
5. Zai-Quan Xu\*, **Noah Mendelson**\*, John A Scott, Chi Li, Irfan H Abidi, Hongwei Liu, Zhengtang Luo, Igor Aharonovich, Milos Toth. Charge and energy transfer of quantum emitters in 2D heterostructures. *2D Materials*, **2020**, 7, (3), 031001.
6. Irfan H Abidi\*, **Noah Mendelson**\*, Toan Trong Tran, Abhishek Tyagi, Minghao Zhuang, Lu-Tao Weng, Barbaros Özyilmaz, Igor Aharonovich, Milos Toth, Zhengtang Luo. Selective Defect Formation in Hexagonal Boron Nitride. *Advanced Optical Materials*, **2019**, 7, (13), 1900397.

## **Co-Author Publications**

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7. Chi Li, **Noah Mendelson**, Ritika Ritika, Yong-Liang Chen, Zai-Quan Xu, Milos Toth, Igor Aharonovich. Scalable and Deterministic Fabrication of Quantum Emitter Arrays from Hexagonal Boron Nitride. *Nano Letters*, **2021**, 21, (8), 3626.

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## Abbreviations

2D	Two Dimensional
3D	Three Dimensional
AB	Ammonia Borane
AFM	Atomic Force Microscopy
APCVD	Atmospheric Pressure Chemical Vapor Deposition
APD	Avalanche Photo Diode
BMIM	1-butyl-3-methylimidazolium hexafluorophosphate
CL	Cathodoluminescence
CVD	Chemical Vapor Deposition
CW	Continuous Wave
EBSD	Electron Backscatter Diffraction
EDS	Energy Dispersive X-Ray Spectroscopy
EMCCD	Electron Multiplying Charge Coupled Device
EPR	Electron Paramagnetic Resonance
EPYS	Environmental Photoelectron Yield Spectroscopy
FDTD	Finite-Difference Time-Domain
FIB	Focused Ion Beam
FT	Fourier Transform
FTIR	Fourier Transform Infrared Spectroscopy
FWHM	Full Width Half Maximum
G/hBN	Graphene/Hexagonal Boron Nitride
HBN	Hexagonal Boron Nitride
HBT	Hanbury Brown and Twiss
HOPG	Highly Oriented Pyrolytic Graphite
HPHT	High Pressure High Temperature
IR	Infrared
LA	Longitudinal Acoustic
LO	Longitudinal Optical
LPCVD	Low Pressure Chemical Vapor Deposition
MBE	Molecular Beam Epitaxy
MOCVD	Metal Organic Chemical Vapor Deposition
MOVPE	Metal Organic Vapor Phase Epitaxy
n	Refractive Index
NA	Numerical Aperture
NIR	Near Infrared
ODMR	Optically Detected Magnetic Resonance
PCC	Photonic Crystal Cavity
PDMS	Polydimethylsiloxane
PEO	Polyethylene Oxide
PL	Photoluminescence
PMMA	Polymethyl Methacrylate
PSB	Phonon Side Band
PVA	Polyvinyl Alcohol
QD	Quantum Dot
QM/MM	Quantum Mechanics/Molecular Mechanics
RPM	Revolutions Per Minute
SCCM	Standard Cubic Centimeters
SEM	Scanning Electron Microscopy

SPE	Single Photon Emitter
SRIM	Stopping and Range of Ion in Matter
TEB	Triethyl Boron
TEM	Transmission Electron Microscopy
TMDC	Transition Metal Dichalcogenide
ToF-SIMS	Time of Flight Secondary Ion Mass Spectrometry
UV	Ultra-Violet
VLS	Vapor Liquid Solid
XPS	X-Ray Photoelectron Spectroscopy
ZPL	Zero Phonon Line

# Abstract

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Emerging quantum technologies are currently limited by the development of robust hardware components to create, distribute, and readout quantum information. Single photon emitters are among the most fundamental components for most quantum information technologies. Among the most promising single photon sources are atom-like systems such as defects in solid-state materials, which can produce on-demand streams of single photons, are suitable for on-chip integration, and offer efficient spin-photon interfaces. As a result, materials such as diamond and silicon carbide have been intensely studied due to their bright and photostable emission, however, efficient integration methods remain a critical challenge.

An intriguing alternative is the use of atomically thin materials which lack dangling bonds allowing for facile integration with nanophotonic components, display extremely efficient light-matter interactions, and be utilized to produce designer quantum states such as by stacking into van der Waals heterostructures. Here I study the 2D material hexagonal boron nitride (hBN) which can host ultra-bright single photon emission arising from point defects in the lattice.

In this thesis I study the bottom-up fabrication of single photon emitters in hBN in great detail, demonstrating the incorporation of bright and optically stable emitters in large scale films comprised of only a few atomic layers. It is demonstrated that during growth we can reduce the inhomogeneous distribution of emission energies by over an order of magnitude and simultaneously control the density of incorporated single photon emitters. The smooth few layer nature of the films enables facile integration with nanophotonic components and with van der Waals heterostructures. I perform emission tuning studies on hBN thin films utilizing both Stark and strain methods, demonstrating record shift magnitudes for a 2D quantum light source, and revealing critical information on the level structure of the emissive defect. Finally, I study the structural nature of the defect finding a carbon based center is likely, a central question which has been debated since their initial discovery in 2015 and demonstrate optically detected magnetic resonance from these defects at room temperature for the first time.