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

**By**

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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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**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

Note * Indicates Equal Authorship

1. **Noah Mendelson**, Dipankar Chugh, Jeffrey R Reimers, Tin S Cheng, Andreas Gottscholl, Hu Long, Christopher J Mellor, Alex Zettl, Vladimir Dyakonov, Peter H Beton, Sergei V Novikov, Chennupati Jagadish, Hark Hoe Tan, Michael J Ford, Milos Toth, Carlo Bradac, Igor Aharonovich. Identifying carbon as the source of visible single-photon emission from hexagonal boron nitride. *Nature Materials,* **2020**.
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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**.
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11. Johannes E Fröch, Sejeong Kim, **<u>Noah Mendelson</u>**, Mehran Kianinia, Milos Toth, Igor Aharonovich. Coupling Hexagonal Boron Nitride Quantum Emitters to Photonic Crystal Cavities. *ACS Nano*, **2020**, 14, (6), 7085.
12. Chi Li, Zai-Quan Xu, **<u>Noah Mendelson</u>**, Mehran Kianinia, Yi Wan, Milos Toth, Igor Aharonovich, Carlo Bradac. Resonant energy transfer between hexagonal boron nitride quantum emitters and atomically layered transition metal dichalcogenides. *2D Materials,* **2020**, 7, (4), 045015.
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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


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.