Nanophotonics with Optically Active Defects in Wide-bandgap Semiconductors

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University of Technology Sydney

Faculty of Science

School of Mathematical and Physical Science

By

Milad Nonahal

Supervisors

Prof. Igor Aharonovich

Dr Mehran Kianinia

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Milad Nonahal, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School 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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Abstract

Quantum nanophotonics offers significant opportunities for all the critical areas of modern quantum technologies, including quantum information processing, quantum sensing and communication. Integrated quantum photonics (IQP) refers to an emerging class of photonic devices that can generate and control coherent quantum states of light and/or matter with quite steadily increasing complexity and scale. Based on the unique properties of quantum mechanics to encode, transmit, and process information, IQP technology provides a path to revolutionize information technology in the near future. One of the fundamental aspects of chip-scale integrated devices is the manipulation of light at the nanoscale, where a quantum emitter can create a quantum state of information. Towards such applications, a robust and high-quality fabrication technique and an efficient integration of quantum emitters are required. Herein, we explored a variety of fabrication and integration techniques for the realization of hybrid and monolithic IQP components in wide bandgap semiconductors. The drawback and benefits of each fabrication and integration techniques were highlighted, and the functionality of the fabrication technique was examined through different characterization methods in four main experimental chapters as outlined below:

In the first experimental chapter, a bottom-up method for monolithic device fabrication from polycrystalline diamond is developed with the realization of single-crystal diamond photonic structures. As a potential tool to achieve emission enhancement, quantum emitters were site-specifically generated into the photonic structure through the patterned growth method. To further explore light/matter interaction, in the following two chapters, we studied the hybrid integration of quantum emitters in 2D material into two different optical cavities resonance namely, whispering gallery modes (WGM) and bound state in the continuum (BIC) modes. We have demonstrated light/matter coupling in weak and strong coupling regimes leading to emission enhancement and rabi splitting, respectively. Finally, as a pathway for the monolithic integration of SPEs, we demonstrated different fabrication techniques to realize a set of common IQP components, including waveguides and cavities.

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Abbreviations

SEM	-	Scanning Electron Microscope
EBL	-	Electron Beam Lithography
FIB	-	Focused Ion Beam
RIE	-	Reactive Ion Etcher
IBE	-	Ion Beam Etcher
IQP	-	Integrated Quantum Photonics
PCC	-	Photonic Crystal Cavity
BIC	-	Bound State In the Continuum
SPE	-	Single Photon Emitter
WGM	-	Whispering Gallery Mode
TIR	-	Total Internal Reflection
ODMR	-	Optically Detected Magnetic Resonance
FWHM	-	Full Width Half Maximum
FDTD	-	Finite Difference Time Domain
SPDC	-	Spontaneous Parametric Down Conversion
1D	-	One Dimensional
HBT	-	Hanbury Brown and Twiss
2D	-	Two Dimensional
3D	-	Three Dimensional
CW	-	Continuous Wave

AFM	-	Atomic Force Microscopy
APD	-	Avalanche Photo Diode
TM	-	Transverse Magnetic
TE	-	Transverse Electric
ZPL	-	Zero Phonon Line
PSB	-	Phonon Side Band
hBN	-	Hexagonal Boron Nitride
PLE	-	Photoluminescent Excitation
QKD	-	Quantum Key Distribution
QIP	-	Quantum Information Processing
MPCVD	-	Microwave Plasma Chemical Vapor Deposition
PMMA	-	Polymethyl Methacrylate
QD	-	Quantum Dot
TMDC	-	Transition Metal Dichalcogenide
SCCM	-	Standard Cubic Centimeter
FSR	-	Free Spectral Range

List of Publications

1) **Milad Nonahal**, Simon J. U. White, Blake Regan, Chi Li, Aleksandra Trycz, Sejeong Kim, Igor Aharonovich, Mehran Kianinia "*Bottom-Up Synthesis of Single Crystal Diamond Pyramids Containing Germanium Vacancy Centers*" Advanced Quantum Technologies, 2021. **4**(7): p. 2100037.
2) **Milad Nonahal**, Chi Li, Febiana Tjiptoharsono, Lu Ding, Connor Stewart, John Scott, Milos Toth, Son Tung Ha, Mehran Kianinia, Igor Aharonovich "*Coupling Spin Defects in Hexagonal Boron Nitride to Titanium Oxide Ring Resonators*" arXiv preprint arXiv:2205.04031, 2022.
3) Mika T. Westerhausen, Aleksandra T. Trycz, Connor Stewart, **Milad Nonahal**, Blake Regan, Mehran Kianinia, and Igor Aharonovich "*Controlled doping of GeV and SnV color centers in diamond using chemical vapor deposition*" ACS applied materials & interfaces, 2020. **12**(26): p. 29700-29705.
4) Chi Li, Johannes E. Fröch, **Milad Nonahal**, Thinh N. Tran, Milos Toth, Sejeong Kim, and Igor Aharonovich "*Integration of hBN quantum emitters in monolithically fabricated waveguides*" ACS Photonics, 2021. **8**(10): p. 2966-2972.
5) Yongliang Chen, Chi Li, Simon White, **Milad Nonahal**, Zai-Quan Xu, Kenji Watanabe, Takashi Taniguchi, Milos Toth, Toan Trong Tran, and Igor Aharonovich "*Generation of High-Density Quantum Emitters in High-Quality, Exfoliated Hexagonal Boron Nitride*" ACS Applied Materials & Interfaces, 2021. **13**(39): p. 47283-47292.
6) Zhao Mu, Soroush Abbasi Zargaleh, Hans Jürgen von Bardeleben, Johannes E. Fröch, **Milad Nonahal**, Hongbing Cai, Xinge Yang, Jianqun Yang, Xingji Li, Igor Aharonovich, and Weibo Gao "*Coherent manipulation with resonant excitation and single emitter creation of nitrogen vacancy centers in 4H silicon carbide*" Nano letters, 2020. **20**(8): p. 6142-6147.