Diamond based nanoelectronics and imaging

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Certificate of Original Authorship

I, Kerem Bray, certify that the work in this dissertation entitled, "Diamond based nanoelectronics and diagnostics", has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also attest that the dissertation has been written by myself. Any help that I have received in my research work and the preparation of the dissertation itself has duly been acknowledged. In addition, I certify that all information sources and literature used are indicated in the dissertation.

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List of Publications

Refereed journal publications

1) **K. Bray**, R. Previdi, B.C. Gibson, O. Shimoni and I. Aharonovich, "*Enhanced photoluminescence from single nitrogen-vacancy defects in nanodiamonds coated with phenol-ionic complexes*", Nanoscale, Vol 11, issue 11, 4869-4874, 2015

2) **K. Bray**, R. Sandstrom, C. Elbadawi, M. Fischer, M. Schreck, O. Shimoni, C. Lobo, M. Toth, I. Aharonovich, "*Localization of narrowband single photon emitters in nanodiamonds*", ACS Applied Materials & Interfaces, Vol 8, issue 11, 7590-7594, 2016. (Chapter 6)

3) **K. Bray**, H. Kato, R. Previdi, R. Sandstrom, K. Ganesan, M. Ogura, T. Makino, S. Yamasaki, A. P. Magyar, M. Toth, I. Aharonovich, "S*ingle crystal diamond membranes for nanoelectronics",* Nanoscale, Vol. 10, 4028-4035, 2018. (Chapter 4 and Chapter 5)

4) **K. Bray**, A. Trycz, R. Previdi, B. Regan, G. Seniutinas, K. Ganesan, M. Kianinia, S. Kim, I. Aharonovich, *"Single crystal diamond membranes containing germanium vacancy centres"*, (arxiv)

5) **K. Bray**, L. Cheung, K. R. Hossain, I. Aharonovich , S. M. Valenzuela, O. Shimoni, "*Versatile Multicolor Nanodiamond Probes for Intracellular Imaging and Targeted Labeling*", Journal of Materials Chemistry B, Vol. 6, 3078-3084, 2018 (Chapter 7)

6) T. T. Tran, J. Fang, H. Zhang, P. Rath, **K. Bray**, R. Sandstrom, O. Shimoni, M. Toth and I. Aharonovich, "*Facile Self-Assembly of Quantum Plasmonic Circuit Components",* Advanced Materials, Vol. 27, issue 27, 4048-4053, 2015.

7) T. T. Tran, **K. Bray**, M. J. Ford, M. Toth and I. Aharonovich, "*Quantum Emission from Hexagonal Nitride Monolayers*", Nature Nanotechnology, Vol. 11, Issue 1, 37, 2016.

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9) T. T. Tran, M. Kianinia, **K. Bray**, S. Kim, Z.-Q. Xu, A. Gentle, B. Sontheimer, C. Bradac, I. Aharonovich, *"Nanodiamonds with photostable, sub-gigahertz linewidth quantum emitters",* APL Photonics, Vol. 2, Issue 11, 116103, 2017 (Chapter 6)

10) S. Häußler, J. Benedikter, **K. Bray**, B. Regan, A. Dietrich, J. Twamley, I. Aharonovich, D. Hunger, A. Kubanek, "*A Diamond-Photonics Platform Based on Silicon-Vacancy Centers in a Single Crystal Diamond Membrane and a Fiber-Cavity"*, ArXiv, 2018.

Conference presentations (Oral)

K. Bray et al., "*Localization of narrowband single photon emitters in nanodiamonds*", Diamond and Carbon Related Materials (DCM), 2016, Montpellier, France.

Received Young Scholar Award for this presentation.

K. Bray et al., "*Localization of narrowband single photon emitters in nanodiamonds*", Conference on Optoelectronic and Microelectroni Materials and Devices (COMMAD), 2016, Sydney, Australia.

K. Bray et al., *"Single crystal diamond membranes for nanoelectronics"*, International Conference of Nanoscience and Nanotechnology (ICONN), 2018, Wollongong, Australia.

Conference presentations (Poster)

K. Bray et al., "Enhanced Photoluminescence from single nitrogen vacancy defects in nanodiamonds coated with phenol ionic complexes", Australian Nanotechnology Network (ANN), 2015, Queensland, Australia.

K. Bray et al., "Enhanced Photoluminescence from single nitrogen vacancy defects in nanodiamonds coated with phenol ionic complexes", International Conference of Nanoscience and Nanotechnology (ICONN), 2016, Canberra, Australia.

K. Bray et al., "Enhanced Photoluminescence from single nitrogen vacancy defects in nanodiamonds coated with phenol ionic complexes", Conference on Optoelectronic and Microelectroni Materials and Devices (COMMAD), 2016, Sydney, Australia.

K. Bray et al., "*Localization of narrowband single photon emitters in nanodiamonds*", Conference on New Diamond and Nano-carbons (NDNC), 2016, Cairns, Australia.

K. Bray et al., *"Versatile Nanodiamond Probes for Intracellular Imaging",* Conference on New Diamond and Nano-carbons (NDNC), 2016, Cairns, Australia.

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List of Abbreviations

Abbreviation	Meaning
AFM	Atomic Force Microscope
APD	Avalanche Photo Diode
BASD	Bead-Assisted Sonication Disintegration
CB	Conductance Band
CHO	Chinese Hamster Ovarian
CL	Cathodoluminescence
CPP	Cell Penetrating Peptide
CVD	Chemical Vapour Deposition
CW	Continuous Wavelength
EBIE	Electron Beam Induced Etching
EL	Electroluminescence
FIB	Focused Ion Beam
FWHM	Full Width at Half Maximum
GaN	Gallium Nitride
GeV	Germanium Vacancy
HBT	Hanbury Brown and Twiss
HPHT	High Pressure High Temperature
DW	Debye-Waller
ICP-RIE	Inductively Coupled Plasma - Reactive Ion Etching
IR	Infrared
LEDs	Light Emitting Diodes
MEM	Micro-Electromechanical System

MPCVD	Microwave Plasma Chemical Vapour Deposition
ND	Nanodiamond
NIR	Near Infra-Red
NV	Nitrogen Vacancy
PL	Photoluminescence
QDs	Quantum Dots
QE	Quantum Efficiency
SCR	Space Charge Region
SEM	Scanning Electron Microscopy
SiC	Silicon Carbide
SiV	Silicon Vacancy
SnV	Tin-Vacancy
SPE	Single Photon Emitter
SPS	Single Photon Source
SRIM	Stopping and Range of Ions in Matter
SIMS	Secondary Ion Mass Spectrometry
STED	Stimulated Emission Depletion
TEM	Transmission Electron Microscope
UV	Ultraviolet
VB	Valance Band
ZPL	Zero Phonon Line

Abstract

To investigate new pathways for numerous quantum technologies it is necessary to efficiently fabricate various interesting materials. Single photon sources that are optically and electrically triggerable are the fundamental building blocks required to push the boundaries of several applications, such as realising secure communication technologies. Accordingly, various platforms are being investigated for generation of single photon emitters (SPEs). Diamond is one platform of great interest, due to its ability to host several photostable, optically active SPE defects that can operate at room temperature. Numerous diamond defects have been studied extensively, including the Nitrogen vacancy (NV), Silicon vacancy (SiV) and, recently, the Germanium vacancy (GeV) colour centres. All were shown to be robust room temperature SPEs. Despite promising reports on quantification and applications of diamond-based defects, the search continues to find an emitter that can excel at most applications.

Another important factor for the utility of colour centres is the method of excitation. While optical pumping is common practice, the ability to electrically excite emitters is highly desired for optoelectronic applications. Several reports exist on the fabrication and characterisation of electrical device structures of various materials, including Gallium Nitride, Silicon Carbide, Zinc Oxide and diamond defects. The central part of the thesis delves into the fabrication of high aspect ratio, thin, nanoscale, conductive diamond membranes hosting SiV colour centres, which demonstrate key advantages, such as being easily transferrable to a variety of structures.

Secondly, I investigate unknown narrowband SPEs in diamond nanocrystals, which are preferable for nanophotonic, quantum communications and bio-imaging applications. The origin of the narrowband emission is determined to be point defects localised at extended morphological defects in individual nanodiamond particles. Furthermore, a highly polarised, narrowband, possessing sub GHz optical linewidths was observed at cryogenic temperatures.

Finally, I exploit the optimal fluorescent, chemical and biocompatibility properties for multi-colour tagging of CHO-K1 and U937 cell lines using both NV^- and, for the first time, SiV diamond colour centres, to investigate their intracellular properties. The non-toxic SiV diamond nanocrystals initially dispersed throughout the cell interior while tagged NV nanocrystals localised close to the nucleus.

Therefore, this work reports new findings in spectroscopic studies of diamond-based colour centres that can be excited optically and electrically. Furthermore, it provides detailed evidence which forms the building blocks for future investigation into diamond-based devices and SPEs for a wide variety of applications. The results presented in this thesis therefore provide a new and interesting platform for applications using defect based nanophotonics.