A fundamental study of epitaxial graphene on silicon carbide on silicon for mid-infrared nanophotonics

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

By

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Abstract

The ability to control light and matter interactions at the nanoscale is a key scope of nanophotonics. In particular, the mid-infrared (MIR) range of the electromagnetic (EM) spectrum hosts several molecular vibrational fingerprints, making it an exciting spectrum for many applications such as exhaled breath detection, cancerous tissue diagnosis, water quality monitoring, greenhouse gas detection, machine vision, and navigation. Plasmonics has enabled sub-diffraction confinement and manipulation of light. However, the high losses and lack of dynamic tunability characterising the conventional metal plasmonics in the MIR ranges represent a bottleneck for further progress.

This work demonstrates that the combination of graphene and silicon carbide can enhance MIR absorption, detected field strength, and confinement. In particular, the possibility of combining the tunable nature of graphene surface plasmon polaritons (SPPs) with low loss surface phonon polaritons (SPhPs) supported in SiC offers great promise. The epitaxial graphene (EG) platform technology on cubic silicon carbide on silicon wafer has substantially advanced over the last decade and offers a straightforward, site-selective, and CMOS compatible platform for developing tailored metasurfaces made of any complex EG/SiC pattern at the wafer -scale.

This thesis combines electromagnetic simulations and experimental characterisations to reveal the fundamental optical properties of EG/SiC/Si using a forest of silicon carbide nanowires grown bottom-up on silicon as a test platform. We first demonstrate that a large wavevectors mismatch between graphene's plasmon and incident photon hinders graphene's SPP mode excitation in a flat EG/SiC/Si system. We overcome this issue by investigating the polariton modes excitation in the core/shell SiC/graphene nanowires system.

By addressing the wavevectors mismatch issue, we demonstrate absorption enhancement of MIR photons and broadening spectral resonances outside the SiC's Reststrahlen band, resulting from the hybridisation of localised SPhP-SPP modes in graphene/SiC nanowires system. Furthermore, we demonstrate extreme subwavelength confinement of the MIR photons within a few nanometers thick oxide layer between graphene and SiC. We also reveal the potential dynamic tunability of hybrid polariton modes in this system. Our simulation results suggest a more compelling need to focus on top-down fabrications of periodically ordered EG/SiC-based metasurfaces to improve further the performance of these material systems towards the MIR nanophotonics.

Certificate of original authorship

I, Patrick Rufangura, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Electrical and Data Engineering, Faculty of Engineering and Information Technology, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference 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.

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Dedication

To Uwiteka Imana Ishobora Byose, my wife Bona Uwera, my daughter Josie A. I. Rufangura, my parents, late Leonidas Rutsindura, and Margueritte Mukankuranga.

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List of Publications

Journal articles

1. **Rufangura, Patrick**, Iryna Khodasevych, Arti Agrawal, Matteo Bosi, Thomas G. Folland, Joshua D. Caldwell, and Francesca Iacopi. "Enhanced Absorption with Graphene coated Silicon carbide Nanowires for Tunable Mid-Infrared Nanophotonics." **Nanomaterials 11, no. 9 (2021): 2339.**
2. **Rufangura, Patrick**, Thomas G. Folland, Arti Agrawal, Joshua D. Caldwell, and Francesca Iacopi. "Towards low-loss on-chip nanophotonics with coupled graphene and silicon carbide: a review." **Journal of Physics: Materials 3, no. 3 (2020): 032005**

Conferences

1. **Rufangura, Patrick**, Arti Agrawal, Thomas G. Folland, Joshua D. Caldwell, and Francesca Iacopi. "Enhanced Absorption with Core/Shell Silicon Carbide/Graphene Nanowires for Tunable Mid-Infrared Nanophotonics." Oral Presentation **In 63rd Electronic Materials Conference (63rd EMC), June 23-25, 2021.**
2. **Rufangura, Patrick**, Arti Agrawal, Matteo Bosi, Thomas G. Folland, Joshua D. Caldwell, and Francesca Iacopi. "Enhanced Mid-Infrared Reflectance with Graphene Coated Silicon Carbide Nanowires." Oral Presentation **In Conference on Lasers and Electro-Optics/Pacific Rim, p. C11E_2. Optical Society of America, 2020.**

Table of Contents

List of Figures

List of Acronyms

EM	Electromagnetic
TE	Transverse electric
TM	Transverse magnetic
EG	Epitaxial graphene
SiC	Silicon carbide
3C-SiC	Cubic silicon carbide
Si	Silicon
NW	Nanowire
LO	Longitudinal optical phonon
TO	Transverse optical phonon
SPP	Surface plasmon polariton
SPhP	Surface phonon polariton
LSPP	Localised surface plasmon polariton
LPhP	Localised surface phonon polariton
FOM	Figure of merit
IR	Infrared
NIR	Near-infrared
MIR	Mid-infrared
FIR	Far- infrared
FTIR	Fourier transformed infrared
ATR	Attenuated total Reflection
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
CVD	Chemical vapor decomposition
CMOS	Complementary metal-oxide-semiconductor
GOS	Graphene on silicon
NA	Numerical aperture
FEM	Finite element method
SNOM	Scanning near field optical microscopy
AREELS	Angle-resolved electron energy loss spectroscopy
HREELS	High-resolution electron energy loss spectroscopy

CST	Computer simulation technology
HFSS	High-frequency structure simulator
PARDISO	Parallel direct sparse solver
MD	Mirror displacement
2D	Two dimensional
CM	Collimating mirror
ILS	Infrared light source
Ph.D.	Doctor of Philosophy
UTS	University of Technology Sydney
TMOS	Transformative Meta-optical systems
INSys	Integrated Nanosystems