

# **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

**Patrick Rufangura**

B.Sc., M.Sc.

School of Electrical and Data Engineering  
Faculty of Engineering and Information Technology

**University of Technology Sydney**

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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.

This research is supported by the Australian Government Research Training Program.

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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

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## Conferences

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## List of Acronyms

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

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