

# An Introduction to Graphene Plasmonics

**P.A.D Gonçalves**

University of Minho, Portugal

**N.M.R Peres**

Univeristy of Minho, Portugal

 **World Scientific**

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

*Published by*

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

*USA office:* 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

*UK office:* 57 Shelton Street, Covent Garden, London WC2H 9HE

### **Library of Congress Cataloging-in-Publication Data**

Names: Gonçalves, P. A. D., author. | Peres, N. M. R., 1967– author.

Title: An introduction to graphene plasmonics / P.A.D. Gonçalves (University of Minho, Portugal), N.M.R. Peres (University of Minho, Portugal).

Description: Singapore ; Hackensack, NJ : World Scientific Publishing Co.

Pte. Ltd., [2016] | 2016 | Includes bibliographical references and index.

Identifiers: LCCN 2016003760 | ISBN 9789814749978 (hardcover ; alk. paper) |

ISBN 9814749974 (hardcover ; alk. paper) | ISBN 9789814749985 (softcover ; alk. paper) |

ISBN 9814749982 (softcover ; alk. paper)

Subjects: LCSH: Plasmons (Physics) | Graphene--Optical properties. | Nanophotonics.

Classification: LCC QC176.8.P55 G66 2016 | DDC 530.4/4--dc23

LC record available at <http://lcn.loc.gov/2016003760>

### **British Library Cataloguing-in-Publication Data**

A catalogue record for this book is available from the British Library.

Copyright © 2016 by World Scientific Publishing Co. Pte. Ltd.

*All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.*

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

In-house Editor: Christopher Teo

Typeset by Stallion Press

Email: [enquiries@stallionpress.com](mailto:enquiries@stallionpress.com)

Printed in Singapore

# Preface

Over the last few years, graphene plasmonics has emerged as a new research topic, positioned at the interface between condensed matter physics and photonics. This still young but rapidly growing field, resulting from the overlap between graphene physics and plasmonics, deals with the investigation and exploration of graphene surface plasmon-polaritons (GSPs) for controlling light-matter interactions and manipulating light at the nanoscale.

In 2011, experimental research in plasmonics in graphene was in its infancy. Some theoretical papers had already been written, but the field was awaiting for some sort of experimental boost. In 2011 a seminal experimental paper (to be discussed in Section 7.1) emerged, demonstrating that plasmonic effects in graphene could be controlled optically, by shining electromagnetic radiation onto a periodic grid of graphene micro-ribbons. This opened a new avenue in graphene physics, launching the new flourishing field of graphene plasmonics. Since then, the field has been witnessing enormous developments at a rapid pace (to be described in Section 1.2).

This is a book on plasmonics in graphene. It grew out of the authors' own interest in the field. Many of the topics covered here refer to problems that were amongst the first to appear in the scientific literature, to which one of the authors has contributed to some extent. Throughout this monograph we have tried to make this book as self-contained as possible, and to provide substantial detail in all derivations. Indeed, with a pencil, some sheets of paper, a dose of enthusiasm, and, at times, a bit of effort, the interested reader should find it easy to reproduce all the results in the book (the Appendices will be most useful for such endeavor). Therefore, we hope that this book will serve as a springboard for any newcomer in graphene

plasmonics. Hopefully, the advanced researcher may also find reasons to keep this book in her/his shelf and to recommend it to her/his students. This is also a book about theoretical techniques to deal with plasmonics in graphene. Many of these techniques have been applied to metal plasmonics before and have been adapted here to tackle plasmonic effects in graphene. The main difference is that metals are described by a complex dielectric function, whereas graphene is described by its complex (non-local whenever necessary) optical conductivity and its sheet (two-dimensional) current.

The book is organized as follows: in Chapter 1 we introduce the theme of the book and present a short review of the literature. We have surely missed some important references and can only hope for the indulgence and comprehension of their authors. This might be specially true in what concerns theoretical and computational work (the literature is already too vast to be covered in a comprehensive way). In Chapter 2 we review some elementary concepts about electronic transport in solids, give a short introduction to graphene's electronic properties, and present some tools to be used later in the book, with particular emphasis on a method to compute the non-local optical conductivity of graphene from the electronic susceptibility in the relaxation-time approximation. Chapter 3 discusses plasmonics at metal-dielectric interfaces and in metal thin films. The results obtained there will be later compared with those found in graphene. Both the semi-infinite metal and the thin metal-film are discussed. In Chapter 4, we finally dive into the field of graphene plasmonics and discuss plasmons both in single- and double-layer graphene. The interesting problem of coupled surface plasmon-phonon-polaritons is also discussed in that Chapter. A short introduction of magneto surface plasmon-polaritons is included, considering both the semi-classical and quantum regimes. We close the chapter with the study of guided (bounded) surface phonon-polaritons in a crystal slab of hexagonal boron-nitride (hBN), a problem very recently considered in the literature and one for which many future developments are expected.

As we shall see, surface plasmons cannot be directly excited in graphene by free propagating electromagnetic waves (as is also the case in planar metal-dielectric interfaces). Thus, in Chapter 5 we review some of the most popular methods of inducing surface plasmon-polaritons in this two-dimensional material (which are also used in traditional metal-based plasmonics). We then move to a detailed study of two methods for exciting plasmons in graphene. These are discussed in Chapters 6 and 7, encompassing the excitation of GSPs by a metallic antenna and by coupling light

to GSPs in a patterned array of graphene ribbons. The discussion of the periodic graphene ribbons system sets the stage for the discussion of the spectrum of surface plasmons in graphene micro-ribbons, micro-rings, and disks. This is done in Chapter 8, where the case of a micro-deformation of the graphene sheet is also discussed, taking as an example the problem of a Gaussian groove. This latter case can be considered an example of nano-structured graphene. These three problems are considered in the electrostatic limit, which turns out to be a rather good approximation when dealing with plasmons in graphene. As we shall show they exhibit scale invariance, a property of the electrostatic limit. It then follows, in Chapter 9, a discussion of the excitation of plasmons by a corrugated dielectric grating, which is a generalization of the single micro-deformation studied in the preceding chapter to the case of a periodic deformation. In this case, the calculation takes retardation into account, but could very well be treated within the electrostatic approximation. Despite some differences, the four methods discussed in Chapters 6, 7, 8, and 9 have in common the decomposition of the fields in a superposition of Fourier modes, either using a Fourier series, for periodic structures, or a Fourier integral for non-periodic systems. In Chapter 10 we discuss how an emitting dipole (for example, a dye, a quantum dot, or a Rydberg atom) can excite graphene plasmons by non-radiative energy transfer from the emitter to graphene. We will see that this is in principle possible, and we compute the non-radiative decaying rate of an emitter. The role of particle-hole processes and excitation of plasmons is discussed separately. We end this Chapter with the calculation of the Purcell factor which encodes information about the total decaying rate of the emitter in the presence of graphene. Finally, in Chapter 11, we conclude with a brief outlook and with the discussion of some topics that have been left out in this book, and which we believe will become rather important in the near future. Also, we have written a number of appendices with either details of the calculations or extensions of the materials discussed in the bulk of the book. To get a flavor of the main ideas, reading the appendices is unnecessary. However, they are a requisite for a working knowledge on the topics discussed in the main text.

Our ultimate hope is that readers may find this book a valuable tool for their study and research in the exciting field of graphene plasmonics and nanophotonics, whether they are currently working on the topic or are about to enter on it. The book's intended purpose is to bring together some of the main topics that are scattered throughout the already vast literature, and to do justice to this alluring field of graphene plasmonics.

To conclude, we further hope that the readers may read this book with the same enthusiasm that we had writing it. Comments, suggestions, and corrections aiming at improving the book for future usage will be most welcome (these can be sent to [peres@fisica.uminho.pt](mailto:peres@fisica.uminho.pt)).

PAULO ANDRÉ DIAS GONÇALVES  
NUNO MIGUEL MACHADO REIS PERES

DEPARTMENT OF PHYSICS  
UNIVERSITY OF MINHO  
BRAGA, 2016