

# Preface

We have started to work in the area of graphene at the end of 2006, discovering that the fascinating Dirac equations could drive to new discoveries in solid-state physics. At that time, although the Dirac equation, which governs the transport of carriers in graphene, was discovered by Wallace long time ago (P.R. Wallace, *The Band Theory of Graphite*, Phys. Rev. 71, 622, 1947), many theoretical issues were still unsolved, and some of them are not solved even today. For instance, the problem of metal–graphene contact resistance, which should clarify how to match two physical systems in which carrier transport is described either by the Dirac equation (graphene) or by the Schrödinger equation (metal), is currently under investigation. In 2006, however, the experiments were in infancy, and the Manchester group led by A. Geim and K.S. Novoselov just published their papers about the amazing electrical properties of graphene (K.S. Novoselov et al., *Electric Field Effect in Atomically Thin Carbon Films*, Science 306, 666, 2004). In a subsequent major publication (M.I. Katsnelson, K.S. Novoselov, A.K. Geim, *Chiral Tunneling and Klein paradox in graphene*, Nature Physics 2, 620, 2006), the Manchester group has cited one of our finest scientific work (D. Dragoman, M. Dragoman, *Optical Analogue Structures to Mesoscopic Devices*, Progr. Quantum Electronics 23, 131, 1999) completely ignored at that time by the scientific community. This paper is at the foundation of our book *Quantum-Classical Analogies*, published in 2004 at Springer, and which can be found in hundreds of libraries worldwide according to WorldCat. The Manchester group has cited us because they discovered that the ballistic transport properties of graphene at room temperature, which manifest over large distances (from few hundreds of microns up to few microns depending on how graphene is encapsulated), can be applied to various electronic devices mimicking optics. Today, after ten years, we can say that we have successfully followed the path of ballistic electron transport-optics analogies, and in the last two years we have experimentally evidenced the first ballistic transistors working at room temperature with impressive electrical and optical properties, and we have developed theoretically the first quantum gates based on ballistic transport. Meanwhile, we have written tens of papers about

graphene devices, reviews, and we have investigated together with our colleagues the first microwave devices based on graphene and the first photodetectors.

Many expectations regarding graphene were immediately spread all over the world, and many groups have started to work in this new area of science. It was thought that in few years graphene will replace silicon, and a new era in applied sciences, especially in nanoelectronics and photonics, will emerge.

However, at that time “the wonder material” could be barely found even in the form of flakes with maximum dimensions of 1 mm or graphene inks. We have obtained some graphene flakes from Peter Blake due to A. Geim, and in this way the long experimental work with graphene has started. We have understood from the beginning that the road to graphene devices will be long and hard. Despite very optimistic reports spread on the net and in many influential journals, we have known since 2008 that from the graphene flakes, which allows you to fabricate 2–3 devices, up to the high degree of integration of Si technology, which is able today to integrate more than 5 billions of transistors, is a long, very long way. Indeed, today integrated circuits based on graphene and containing 3–4 devices are a rarity, although graphene wafers of 4 in. and even 6 in. are fabricated by companies such as Graphene Laboratories, known also as Graphene Supermarket, or Graphene Industries, with which we cooperate since five years. Why? There are two main ways to grow graphene: via CVD, which requires a transfer of graphene grown on copper on a certain substrate, or via epitaxial growth on SiC at very high temperatures. If you examine such a wafer on SEM, you will find cracks, wrinkles, and defects in many places of the wafer. If we fabricate a device on such a wafer, the yield is 30–60% depending on the substrate. This is the main reason why graphene and many other atomically thin materials cannot compete with Si technology yet, although a lot of money is invested in the research. Moreover, if now graphene devices have gained a certain maturity, this is not the case for other 2D materials, where flakes are still used and devices at the wafer level are still a rarity.

We have reflected a lot if it is necessary to write a book about graphene and other 2D materials, their physics, and applications, since the subject is still immature despite thousands of published papers, and theoretical works prevail too much over experimental results. The best book about graphene theory in our opinion is the book of M.I. Katsnelson, *Graphene-Carbon in Two Dimensions*, Cambridge Univ. Press, 2012. However, a book about devices based on graphene and other 2D materials and their physics is still missing, the results being spread in papers and/or books edited by various editors.

The present book is divided into three chapters. The first and main chapter, containing about 50% of the book, is dedicated to graphene devices such as transistors, diodes, sensors, integrated circuits, optoelectronic circuits, and biosensors based on graphene. The remaining two chapters are dedicated to other 2D materials, especially to transition metal dichalcogenides (TMDs), and describe their physics, growth techniques, and devices based on them, such as transistors, photodiodes, tunneling diodes, memristors, and even elementary circuits. Many figures, maybe in excess, accompany the explanations. The book was written having in mind many

Ph.D. students, postdocs, and young researchers, which need to absorb a lot of new knowledge, not taught at universities, in a rather short time.

The book is written with the hope that this ultimate research area in applied physics, dealing with atomically thin materials, will evolve and develop in the next years. The maturity of the growth processes of graphene and other 2D materials is the main challenge for the years to come. No serious application will be developed until hundreds of devices will be fabricated on the same wafer, and the reproducibility will be comparable to that in semiconductors.

Graphene is zero-bandgap semiconductor. Therefore, designing and fabricating devices that are analogous to semiconductor devices is a straightforward, but many times unsuccessful way to develop new applications. The best example is the transistor, which originates from semiconductor physics. The lack of a bandgap in graphene results in graphene transistors to underperform compared to their semiconductor counterparts, due to the lack of a saturation region and the lack of an off state. So, graphene transistors are not suitable for digital applications and cannot be used as amplifiers beyond few GHz, although better graphene quality and clean fabrication processes could increase the frequency up to 1 THz, especially when ballistic transport is used. On the other hand, opening a bandgap in graphene destroys its main attractive properties, such as high mobility or temperature independence of its physical parameters.

The main idea for developing nanodevices based on atomically thin materials is to use specific physical properties of 2D materials and to develop specific devices based on them. All semiconducting devices originate from semiconductor physics. Therefore, new devices should result from the new physics of atomically thin materials. For example, the ballistic transport and/or the nonlinear electromagnetic properties of graphene can be used for innovative devices in electronics and optics. Or, the large effective mass in TMDs can be exploited to reduce the detrimental effects in transistors with gate length of 5 nm and even less.

We hope that in few years, the devices based on atomically thin materials will fully exploit their unprecedented physical properties as well as the possibility to scale down electronic devices to atomic scale. The first such device—a transistor based on a single atom—was recently reported. Moreover, the ultimate computer will be based on atomic switches, which are now under development in the area of memristors and artificial learning. Thus, the adventure to atomic scale electronics has just started.

We are deeply indebted to our colleagues and friends with whom we have worked these years and have shared ideas and experience. Many thanks to Dr. George Konstantinidis and Dr. George Deligeorgis from FORTH, Heraklion, who have fabricated the first graphene devices on flakes, Prof. Dan Neculoiu, who has modeled and measured together with us the first microwave devices ever made on graphene, Dr. Antonio Radoi, who fabricated one of the first graphene photodetectors using a small bottle of graphene ink received for free from Nanointegris, Prof. Hans Hartnagel, with whom we have designed the first electronic THz graphene emitters and multipliers, Dr. Peter Blake, who provided us with the first graphene flakes and continues to do it, and to Dr. Mircea Modreanu, from whom

we learned oxide physics and fabrication tricks. Many thanks also to our colleagues from the NanoRF project and FP7 project founded by EU, who shared with us novel ideas and methods.

Many thanks to many unnamed colleagues, who encouraged us to work in the area of the physics and devices based on atomically thin materials. This book, involving ten years of intense research, short holidays, and few weekends, is dedicated to all of them.

Last, but not least, we thank Dr. Claus Ascheron, who is the editor of our books since 1998. He has trusted us from the beginning, and we hope that this book will please him as have the other four books previously published at Springer in various editions.

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