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Editorial

Two-Dimensional Electronics — Prospects and Challenges

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1. Introduction

For about a decade, 2D (two-dimensional) materials have represented one of the hottest directions in solid-state research. The rise of 2D materials began in 2004, when the Novoselov–Geim group from the University of Manchester and the group of Berger and de Heer from Georgia Tech published their pioneering papers on graphene, a 2D material consisting of a single layer of carbon atoms arranged in a honeycomb lattice [1,2]. Since graphene shows outstanding properties, e.g., very high carrier mobilities, excellent heat conductivity, and superior mechanical strength, researchers from various communities including physicists, chemists, material scientists, electronics engineers, *etc.*, became fascinated by this new material. An impression on the unabatedly strong interest in graphene can be obtained by counting the papers listed in the database Web of Science [3] under the search term "graphene". For 2004, one finds 183 entries compared to over 7000 for 2010 and more than 34,300 for the year 2015, which exceeds the number for 2014 by more than 5000.

2. From Graphene to Beyond Graphene

Many of the early papers on graphene envisaged its use in electronics as most promising [2,4]. This has spurred expectations that graphene could become the perfect material for transistors and possibly replace the conventional semiconductors. Consequently, many groups worldwide started working on graphene transistors, and the first graphene MOSFET (metal-semiconductor field-effect transistor) was demonstrated in 2007 by Lemme [5], one of the authors of the present Special Issue, and integrated graphene circuits have been successfully fabricated [6]. Meanwhile, however, the prospects for graphene for electronic applications, in particular for transistors, are assessed less optimistically. The main problem is that graphene does not possess a bandgap. As a consequence, graphene MOSFETs cannot be switched off (note that switch-off is mandatory for transistors to be used in digital logic) and their RF (radio frequency) performance is degraded [7,8]. However, research on graphene transistors is still underway, and the use of graphene transistors for specific applications is still on the agenda.

Possibly even more important than the work on graphene transistors is the fact that the advances in graphene research have motivated scientists to extend their work to 2D materials beyond graphene. A milestone in this direction was the demonstration of the first MOSFETs with single-layer MoS_2 channels by the Kis group in 2011 [9]. Meanwhile, hundreds of 2D materials beyond graphene have been discovered—many of them possess sizeable bandgaps and, therefore, are potentially useful for electronics [10–13]. This has led to intensive research on the application of 2D materials beyond graphene in the More Moore domain of semiconductor electronics, *i.e.*, digital complementary MOS, and in the More Than Moore domain.

3. The Present Special Issue

This Special Issue comprises a total of 12 papers (four review papers and eight contributed articles) and spans a wide range of topics, which extend from first principle band structure calculations [14] and molecular dynamics simulations of the thermal properties [15] of 2D materials, over numerical simulations and compact modeling of 2D transistors [16–18] and other 2D devices [19,20], 2D material growth [21,22] and processing issues [22–24], up to experimental 2D devices and their applications [22,23,25]. Regarding the materials, the papers of the Special Issue deal with graphene and graphene nanoribbons [16–20,22,23,25], TMDs (transition metal dichalcogenide) [14,21,22,24,25], phosphorene, which frequently is called 2D black phosphorus [24,25], and 2D metal oxides [25]. Finally, the papers discuss More Moore electronics and transistors [16–18], as well as applications belonging to the More Than Moore domain of semiconductor electronics, including optoelectronics [22], RF electronics [16,23], sensors [20,25], and field emitters [19].

Li and Östling provide an excellent overview of the status of 2D material synthesis [21] and put special emphasis on the scalability of the discussed techniques and the attainable 2D material quality. Yogeesh and coauthors review their recent progress on flexible graphene devices and demonstrate a flexible graphene-based radio frequency receiver operating at 2.4 GHz [23]. Bablich, Kataria, and Lemme present a thorough overview on the application of 2D materials in optoelectronics [22], and, in the last review paper, Varghese and coauthors comprehensively discuss the use of 2D materials for gas sensors [25].

Kuc and Heine investigate the stability and electronic structure of monolayer TMD alloys [14]. Khan and coauthors study the thermal conductivity of graphene nanoribbons using molecular dynamics simulations [15]. Rubio-Bollinger and coworkers experimentally investigate the visibility of exfoliated TMD and black phosphorus flakes on different substrates, and show that, compared to the most frequently used SiO_2/Si substrates, Si_3N_4 on Si provides a significantly increased optical contrast, which makes the identification of 2D flakes much easier [24].

The next three papers are devoted to the simulation of advanced graphene-based transistors. Banadaki and Srivastava investigate the effects of band-to-band tunneling and edge roughness on the behavior of graphene nanoribbon MOSFETs [18]. Nanmeni Bondja and coworkers study the steady-state and RF performance of graphene nanoribbon transistors by numerical device simulations [16]. Finally, in the third transistor paper, Fregonese and coauthors describe a compact modeling approach for a novel graphene-based transistor type called graphene base transistor [17]. Finally, two papers discuss several aspects of the application of graphene in non-transistor devices. Natsuki analyzes graphene nanomechanical mass sensors [20] and Fursey and coworkers discuss graphene-based field emitters [19].

4. Outlook

Compared to conventional semiconductors, such as Si and III-V compounds, the group of the 2D materials is still in its infancy, and many problems have still to be solved for these materials to be used in commercial electronic devices and circuits. This makes it currently difficult to identify the most promising applications for 2D materials. On the other hand, within only a few years, substantial progress has been achieved. This makes me confident that 2D materials will find their applications, in particular, given the fact that electronics comprise much more than transistors. A few examples are given below.

Two-dimensional materials are bendable and, therefore, ideally suited for the emerging field of flexible transistors and circuits [26]. Applications for the 2D materials beyond transistors are, for example, touch screens and batteries. In November 2013, the Chinese smartphone maker AWIT announced the shipment of 2000 AT26 equipped with a graphene touch screen [27] and in March 2015, a consortium of two Chinese companies, the graphene maker Moxi and the tablet maker Galapad, announced the shipment of 30,000 of the Android Settler α smartphones, which use graphene for the screen, battery, and heat conduction [28]. Additionally, Samsung, one of the big players in the smartphone business, is working intensively on the application of graphene in mobile phones.

Research on 2D materials, both graphene and beyond graphene, will remain an exciting field for many years to come. According to Kroemer's Lemma of New Technology [29], which reads as "The principal applications of any sufficiently new and innovative technology always have been—and will continue to be—applications created by that technology", we should be prepared to see a great many of new applications for 2D materials, which, at least in part, have not yet been envisaged.

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