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Review report
on the habilitation thesis
„Epitaxial Graphene on Silicon Carbide"
by RNDr. Jan Kunc, Ph.D.

The habilitation thesis submitted by Dr. Jan Kunc consist of a collection of 15 already published scientific papers supplemented with a commentary, in fulfillment of the requirements according to section 72, subsection 3 of the Higher Education Act.

The thesis itself starts with a short introduction, where Dr. Kunc explains his different stations during his career and how he got interested and involved in the scientific field of graphene in general and epigraphene (or epitaxial graphene) on silicon carbide (SiC) in particular. From that point of view, I would rather call this section an preface. The real introduction into the topic of graphene can be found in section 1, which is entitled "A Brief History of Graphene". This section gives a concise overview over the major breakthroughs in the field of graphene. Unlike many other authors, Dr. Kunc does not restrict this overview to the time after the probably most famous papers by Geim and Novoselov from 2004. Instead, he also includes work done well before that time and/or by other authors. I think this section is very well done. In section 2 the basic properties of graphene are reviewed and discussed. Dr. Kunc describes the tight-binding model of the graphene π-bands and introduces into the Berry's phase, the Dirac equation and how it relates to charge carriers in graphene, the spectrum of Landau levels that are formed in a magnetic field, and the optical properties of graphene. Furthermore, possible applications of graphene are mentioned. Section 3 is concerned with the preparation of graphene, mainly (but not exclusively) focusing on the growth of graphene on SiC. Section 4 with the title "Epitaxial graphene allotropes" explains different structures of graphene that can be obtained on SiC. Section 5 is dealing with the 15 publications included in the habilitation thesis. For each paper, Dr. Kunc provides a short explanation of the basic idea bind the work and describes his contribution to the work. 12 papers deal with graphene while two further papers deal with 2DEGs in CdTe and CdMnTe quantum wells and one with radiation detectors, indicating additional research interest beyond the main topic graphene. Section 5 is followed by a list of the 15 papers and a section entitled "Conclusion". Here Dr. Kunc provides a brief summary of the thesis and comments on the position of graphene in the field of 2D materials. The bibliography is followed by the reprints of the 15 above mentioned

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publications. These publications form the body of scientific work done by Dr. Kunc during the last years.

Paper 1 with title “Effect of Residual Gas Composition on Epitaxial Growth of Graphene on SiC” (Physical Review Applied 8 (2017) 044011) reveals how the growth of epigraphene on SiC is influenced by residual water in the growth environment. One of the unique features of the work is the use of a residual gas analyzer to monitor gas phase composition. The conclusion of the paper concerns the purity of the Ar gas used and its flow rate, which is an important ingredient for growing high quality graphene.

The second paper included in the thesis is entitled “Thickness of sublimation grown SiC layers measured by scanning Raman spectroscopy” (Journal of Alloys and Compounds 789 (2019) 607). SiC wafers, which are the growth substrate for epigraphene, are frequently n-type doped and conducting at room temperature. Insulating SiC can be obtained by additional doping with vanadium. The paper shows that scanning Raman spectroscopy can be employed to determine the thickness of homoepitaxially grown, high-resistivity, V-doped SiC layers on n-type SiC wafers, which is otherwise difficult to perform in an non-destructive way.

“Raman 2D Peak Line Shape in Epigraphene on SiC” is the title of paper 3 (Applied Sciences 10 (2020) 2354). It demonstrates different contributions to the broadening of the 2D peak. Lifetime (homogeneous) broadening causes a Lorentzian broadening while inhomogeneities cause an Gaussian (inhomogeneous) broadening. The main contribution to the latter was found to be caused by locally varying strain. Hydrogen intercalated buffer layer (QFMLG) was observed to have the smallest homogeneous and inhomogeneous 2D peak broadening.

Paper 4 with the title “Controlled epitaxial graphene growth within removable amorphous carbon corrals” deals with an approach for the structured growth of graphene on SiC. Amorphous carbon structures are fabricated on SiC using lithographic methods. The structures influence SiC step bunching and act as step flow barriers, allowing the formation of step-free area homogeneously covered with graphene. This work represents an important contribution to the realization epigraphene devices.

In the fifth publication “Planar Edge Schottky Barrier-Tunneling Transistors Using Epitaxial Graphene/SiC Junctions” (Nano Letters 14 (2014) 5170), multilayered epitaxial graphene (MEG) on the C-face of SiC is employed in a planar graphene/SiC field effect transistor. The MEG thereby provides 1D tunneling barriers to the SiC which forms the channel due to an accumulation layer. The device showed excellent on-off ratios and sustains large current densities.

In a further paper with the title “A method to extract pure Raman spectrum of epitaxial graphene on SiC” (Applied Physics Letters 103 (2013) 201911) proposes a novel, useful method for the evaluation and processing of Raman spectra. The method relies on a non-negative matrix factorization approach. The capabilities of the method to separate the Raman spectra of epitaxial graphene on SiC into the spectra of graphene and the substrate is demonstrated.

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“A wide-bandgap metal–semiconductor–metal nanostructure made entirely from graphene” is the title of paper 7 (Nature Physics 9 (2013) 49). It reports the electronic properties of graphene grown at the side walls of trenches made on SiC substartes via lithography. It is observed that 1D graphene nanoribbons with a gapped electronic band structure are formed at the side walls. The approach allows the self-assembly of well-defined semiconducting graphene nanoribbons without the need for cutting the ribbons out of extended graphene sheets by mans of lithography.

Paper number 8 carries the title “Hydrogen intercalation of epitaxial graphene and buffer layer probed by mid-infrared absorption and Raman spectroscopy” (AIP Advances 8 (2018) 045015). It investigates in detail the formation of Si-H bonds and the structure of the SiC/graphene interface during H-intercalation below the so-called buffer layer. In addition, the stability of the hydrogen layer is studied. The paper conveys valuable information about the intercalation process.

Another paper with the title “The electroluminescent properties based on bias polarity of the epitaxial graphene/aluminium SiC junction” (Journal of Physics D: Applied Physics 51 (2018) 265104) investigates the electrooptical properties of the graphene /SiC interface. Here, radiation is emitted due to electron-hole recombination in the proximity of the graphene/SiC interface.

Vibrational properties of the buffer layer are studied in paper 10, “ZO phonon of a buffer layer and Raman mapping of hydrogenated buffer on SiC(0001)” (Journal of Raman Spectroscopy 50 (2018) 1). In this work the ZO phonon of the buffer layer at M and Γ of the Brillouin zone is identified. This phonon is responsible for the charge carrier scattering in graphene on the buffer layer. Furthermore, strain and homogeneity of the quasi-freestanding graphene are investigated.

Paper 11 introduces a new method to determine the quality of large area graphene samples. It carries the title “Contactless millimeter wave method for quality assessment of large area graphene” (2D Materials 6 (2019) 035028). To that end, transport measurements were compared to the results of contactless microwave absorption data and a favorable agreement between different parameters extracted from the experiments was observed. The work demonstrates that the nondestructive microwave absorption is a valuable characterization technique for graphene and related 2D materials in a production environment.

In the publication “Detachment of epitaxial graphene from SiC substrate by XUV laser radiation” (Carbon 161 (2020) 36) the effect of sub-nanosecond ($t < 100$ ps) XUV pulses ($\lambda = 21.2$ nm) on graphene on SiC was studied. For fluences between $0.4 - 0.7\ \mathrm{J/cm^2}$ a detachment of the graphene including the buffer layer was observed. At higher fluences the underlying SiC undergoes amorphization as well. No modifications are observed at lower fluences and it was argued that a eversible breaking of the van-der-Waals bonds between SiC graphene and bufferlayer occurs.

The remaining three publications relate to topics beyond graphene. In the paper “Enhancement of the spin gap in fully occupied two-dimensional Landau levels” (Physical Review B 82 (2010) 115438) a 2DEG in a CdTe quantum well is investigated by polarization-resolved magnetoluminescence as well as magnetotransport measurements. The influence of many-body interactions on the spin splitting of occupied Landau levels was observed, which depends on the spin polarization of the 2DEG.

Paper number 14 “Magnetoresistance quantum oscillations in a magnetic two-dimensional electron gas” (Physical Review B 92 (2015) 085304) investigates Shubnikov-de Haas oscillations of 2DEGs in CdTe and CdMnTe quanum wells. The effect of the magnetic Mn ions in CdMnTe is discussed. Its influence is revealed by a beating pattern on the quantum oscillations.

The last paper of the collection with the title “Efficient Charge Collection in Coplanar-Grid Radiation Detectors” (Physical Review Applied 9 (2018) 054020) contains a theoretical study in which the response of an radiation detector is modeled.

All these papers have been published in scientific journals with very good to excellent reputation. They describe scientific work on a very high level and contribute significantly to the development of the research fields either by providing new information on materials properties and the underlying physics, by improving existing or proposing new methods, or by suggesting/demonstrating new applications. The plagiarism report provided by to me gives no indication of plagiarism in the work presented by Dr. Kunc.

The collection of papers clearly demonstrates the excellent capabilities of Dr. Kunc as a scientist. I have only one minor proint of criticism here. I think it would have been nice if Dr. Kunc would have provided some more guidance to the reader on how the different topics of his scientific work, which are presented in these publications, are connected together. This could have been included in section 5 of the thesis. However, this minor criticism does not prevent me from my recommendation to accept the habilitation thesis.

Sincerely,

[redacted]

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P.S.: Two minor editorial comments:

1. The caption of fig. 2.5 doesnot fit to the figure.
2. In the bibliography there are many occasions, where the capitalization of letters is wrong. For example “sic” should be replaced by “SiC”, “6h-“ by “6H-“, “c-face” by “C-face”, and so on.