

ROADMAP 2D MATERIALS



TABLE OF CONTENTS

VISION	2
FOCUS AREAS	3
Focus area - FUNDAMENTALS	4
Focus area - MULTIFUNCTIONAL COMPOSITES AND COATINGS	7
Focus area - ELECTRONICS AND PHOTONICS	10
Focus area - ENERGY APPLICATIONS	13
Focus area - BIO APPLICATIONS	15
REQUIERED FUTURE STEPS	17
INTERNAL ADVISORY AND STEERING BOARD	18
RESEARCHERS	19

VISION

As the coordinating university of the Graphene Flagship Chalmers has already reached an outstanding visibility worldwide for the graphene research. Presently **more than 40 senior researchers across six different departments** are doing research on graphene and related 2D materials. The explored scientific questions cover fundamental research including physics, chemistry, and materials science and application-oriented research in the same fields aiming at the design of novel technologies.

The Graphene Centre at Chalmers (GCC) has the goal to gather all research at Chalmers on atomically thin 2D materials, including graphene, transition metal dichalcogenides and other layered materials as well as related van der Waals heterostructures. GCC addresses Chalmers' researchers and students as well as industry partners in the region. It provides a **forum for 2D material researchers** to exchange ideas, to identify synergy effects, to build new and strengthen already existing collaborations within Chalmers, and finally to coordinate joint applications for larger grants. GCC also offers a **platform for industry partners and researchers** to discuss current challenges in technology, to identify the industrial needs for specific research directions, and to start joint academy-industry projects. Finally, GCC offers a **meeting place for postdoctoral researchers, PhD students and master students**, who already are or who would like to be involved in 2D material research with the aim to exchange ideas and problems, identify synergy effects and initiate collaborations amongst research groups at Chalmers.

The vision of the GCC is for Chalmers to be one of the leading research institutions in the field of atomically thin 2D materials and related heterostructures.

FOCUS AREAS

The research at Chalmers on atomically thin 2D materials is divided in five focus areas:

FUNDAMENTALS

Theoretical and experimental research within the areas of optics, transport, non-equilibrium dynamics as well as synthesis of 2D materials. The aim is to uncover **elementary processes** and to exploit the insights to predict **novel technology concepts**.

MULTI-FUNCTIONAL COMPOSITES AND COATINGS

Exploit the remarkable properties of 2D materials (light, flexible, strong, excellent conductivity of heat and current) for **multi-functional** composite and coating applications in automotive, airplane, packaging and related industries.

ELECTRONICS AND PHOTONICS

Explore the possibilities for the design **high performance flexible and ultrathin** electronics and photonics devices based on 2D materials including light-emitting, light-detecting, and light-amplifying devices.

ENERGY APPLICATIONS

Usage of layered 2D materials for efficient energy conversion in solar cells and **energy storage** in batteries.

BIO APPLICATIONS

Exploit the optimal surface-to-volume ratio to design **highly sensitive biosensors** and explore the possibility to apply 2D materials as **antibacterial coatings**.

Fundamentals

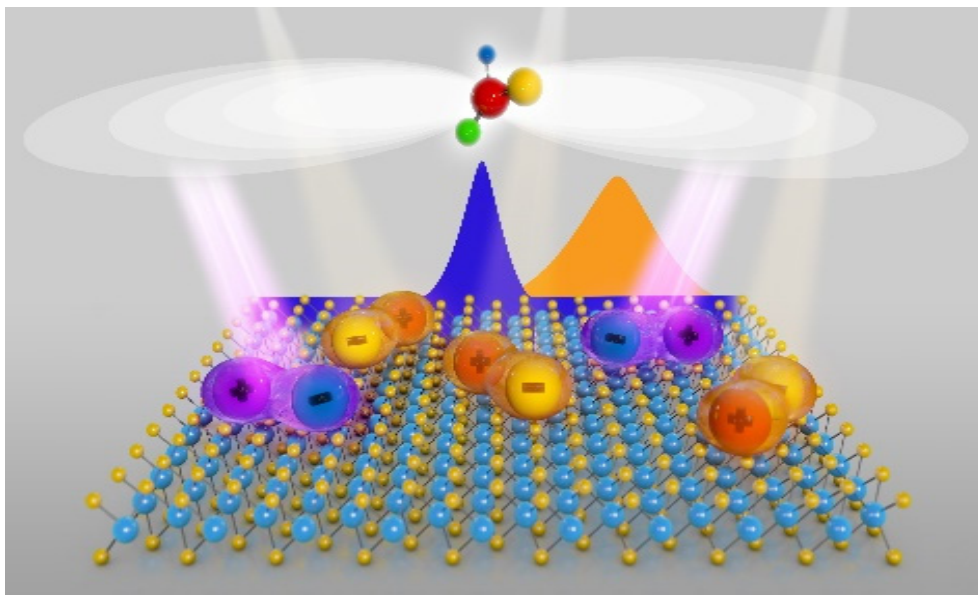
Multifunctional
Composites &
coatings

Electronics
and
Photonics

Energy
Applications

Bio
Applications

FOCUS AREA – FUNDAMENTALS



Dark exciton states in TMD monolayers can be activated in presence of molecules suggesting novel exciton-based molecules sensors [E. Malic].

Present status

The focus area of fundamentals covers multidisciplinary research on 2D materials and related van der Waals heterostructures aiming at new physical phenomena and technological applications. Researchers take particularly advantage of the availability of a large number of 2D materials with a wide range of properties, such as:

- (i) atomically thin structures and high-mobility Dirac electrons in graphene,
- (ii) semiconducting, large spin-orbit coupling and fascinating exciton landscape in transition metal dichalcogenides (TMDs) including bright and dark excitonic states
- (iii) insulating properties of h-BN,
- (iv) dielectric, magnetic and superconducting materials, and (v) spin-momentum locking and Dirac or Weyl fermionic states of topological insulators and Weyl semimetals. In addition to the individual monolayer materials, van der Waals heterostructures based on these materials are used to tailor their properties, which opens a promising platform for studying the proximity-induced effects at the atomic scale.

The primary goal of the focus area fundamentals is to demonstrate significant scientific breakthroughs by fabricating novel 2D materials and related heterostructures, developing sensitive characterization techniques and devices for probing new phenomenon, and fundamental understanding of the associated microscopic mechanisms by theoretical calculations. There is a unique state-of-the-art nanofabrication, characterization and computational infrastructure and an

excellent research environment with an integrated approach on research, education and innovation on 2D materials.

The experimental research focuses on electronic charge, spin, thermal and quantum transport phenomenon (Sergey Kubatkin, Avgust Yurgens, Saroj Dash, Jie Sun, Samuel L. Avila), spintronics (Saroj Dash), superconductivity and Majorana physics (Florian Lombardi, Thilo Bauch), high frequency measurements (Andrei Vorobiev, Jan Stake), optics and plasmonics (Timur Shegai), and electron microscopy (Eva Olsson). The theoretical research focuses on development of first-principle methods and analytical calculations (Per Hyldgaard, Elsebeth Schröder, Paul Erhart, Itai Panas, Valentina Cantatore), microscopic modelling of carrier dynamics and exciton physics (Ermin Malic), quantum transport theory (Tomas Löfwander), optical processes and plasmons combined with charge transport (Jari Kinaret, Mikael Fogelström), mechanical and thermal properties (Andreas Isacsson), and non-local response of graphene and graphene plasmons (Philippe Tassin).

Strengths and challenges

The strength of the experimental and theoretical research is built upon recent successful development of preparation, characterization and device design based on 2D materials and related heterostructures. Chalmers includes internationally known researchers with strong international network and with innovative approaches to up-to-date research questions. We are involved in EU Graphene Flagship, Graphene FlagEra, H2020 collaborative projects, as well as a number of national initiatives. Breakthrough results on 2D materials are published in high impact journals such as Nature Nanotechnology, Nature Physics, Nature Communications, Advanced Materials, Nano Letters, Physical Review Letters, etc.

Conducting research on fundamentals in the advanced and highly competitive field of 2D materials requires PhD and postdoc researchers, materials' growth facilities, and sensitive measurement tools. Lack of funding for man-power is a major concern among researchers and competition with much larger groups in EU, USA, Japan with a better access to funding is very challenging. Furthermore, presently there are no growth facilities for preparation of 2D materials beyond graphene, and there is a lack of measurement facilities for ultrafast optics and low-temperature magneto-optics.

Short-term goals

The aim is to explore and exploit the unique properties of 2D materials and related heterostructures that are expected to give rise to novel physical phenomena and establish a strong experiment-theory environment. In particular, we see the following goals:

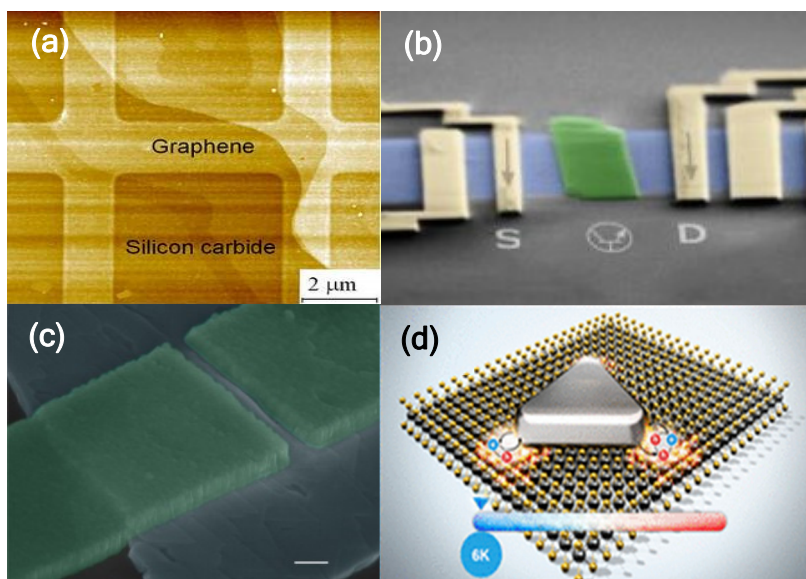
- Growth of graphene, semiconductors, topological insulators, Weyl semimetals and their van der Waals heterostructures by CVD and epitaxy methods,
- Proximity-induced interactions and interface related electrical, spintronic, optical, superconducting, magnetic and topological quantum effects in heterostructures,
- Epitaxial graphene for metrology, sensing and electronics,

- New concepts for non-equilibrium thermoelectric, optoelectronic and plasmonic effects,
- Exploiting dark exciton phenomena for sensing and optoelectronics,
- Development of terahertz power detection mechanisms,
- Develop theory for understanding thermal rectification and flexo-acoustic-electric effects,
- Electron and spin transport in graphene nanodevices for all-carbon electronics,
- Spintronic and Josephson effects in topological insulators.

Long-term goals

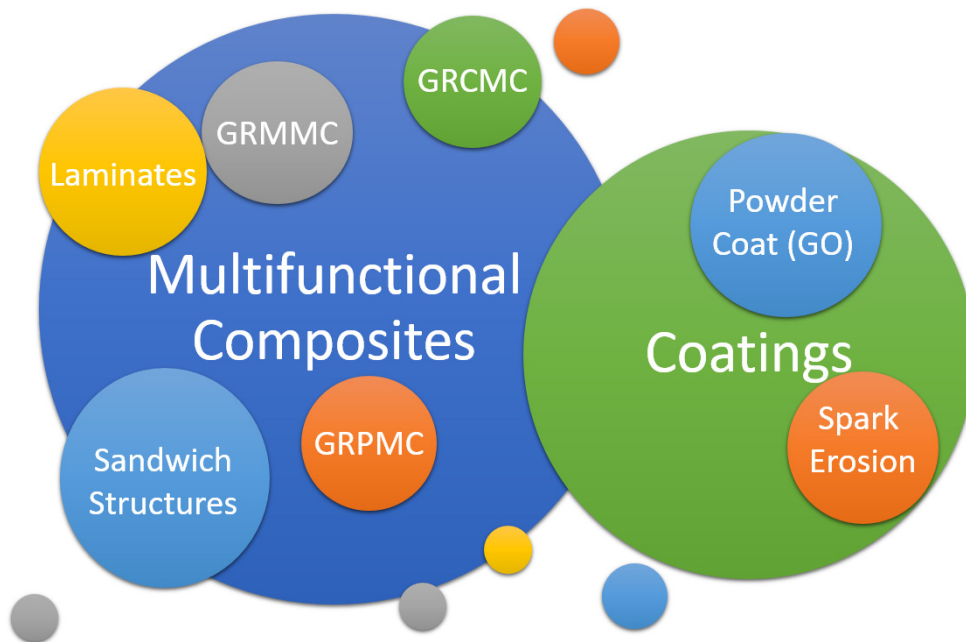
The long-term goals are to use fundamental studies to address larger scientific challenges and to aim for practical applications:

- Large area growth of van der Waals heterostructures and their practical applications in electronics, optoelectronics, spintronics and quantum technology,
- Establish the basis for state-of-the-art millimetre-wave and terahertz electronic devices,
- Proximity to strong-coupling superconductors and tunnelling thermoelectricity,
- Establish framework for non-equilibrium thermos elasticity of 2D materials,
- Couple plasmons with excitons or polaritons in 2D materials heterostructures for novel sensors or optical components,
- Realization of robust topological quantum effects such as quantum spin Hall and anomalous Hall effects at elevated temperatures,
- Topological superconductivity, Majorana and spin physics for quantum technology,
- Establish a consistent approach involving density matrix and density functional theory calculations to be able to model photo-detecting, -emitting and -amplifying devices.



(a) SEM picture of epitaxial graphene quantum Hall device; (b) CVD graphene/ MoS2 spintronic device; (c) Topological super-conductor device; (d) Schematics of a WS2 for exciton-plasmon interaction. [S. Kubatkin, S. Dash, F. Lombardi, T. Shegai].

FOCUS AREA – MULTIFUNCTIONAL COMPOSITES AND COATINGS



Schematic illustration of different research fields within the focus area multifunctional composites and coatings.

Present Status

Composite materials are at the moment the only application of graphene that has reached full industrial scale. Currently there is a strong interest from industries, and this interest will likely expand further in Sweden and abroad. However, the strong industrial interest causes misinformation, where a number of small companies and research groups claim large-scale production and breakthrough applications. This proliferation of hype renders difficult for industries to establish effective, long-term collaborations.

The Focus Area on Multifunctional Composites and Coatings includes two large research fields: Multifunctional Composites, which includes: Graphene Reinforced Metal matrix composites (GRMMC), graphene reinforced polymer matrix composites (GRPMC), graphene reinforced ceramic matrix composites (GRCMC), composites laminates (layered structures), and sandwich structures (consisting of stiff facesheets and light weight core); and Coatings, which includes: powder coating of graphene oxide (GO) and spark erosion (electrical discharge machining), among others. Research on multifunctional composites and coatings is being performed within GCC by Andreas Isacson, Brina Blinzler, Christian Müller, Eva Olsson, Johan Liu, Lars Nyborg, Leif Asp, Luping Tang, Ragnar Larsson, Roland Kádár, and Vincenzo Palermo.

Strengths and Challenges

Chalmers is in an ideal position to have a key role in the future development of Graphene Reinforced Matrix (GRM) based multifunctional composites and coatings. We can take advantage of strong connections with industries in the region (e.g. automotive, aerospace, packaging), several groups currently active in the field of graphene, and many others featuring a strong know-how in fields where graphene will make a difference (carbon fibre composites, energy transport and storage, thermoplastics etc.). GCC will thus have a key role in this field, fostering knowledge transfer and collaboration between groups who have expertise in graphene fabrication and processing with groups and industrial partners pursuing composites and coatings for structural reinforcement, heat, charge transport, energy storage etc. For composite applications, a challenge lies in the quality of the graphene used. It is also important to develop demonstrator materials in order to raise the Technology Readiness Level (TLR) of GRM technologies. Competence in functionalization is key to creating an appropriate interface between the 2D additive and the matrix material. A composites processing laboratory, built during summer 2018, is available to researchers in Chalmers Graphene Centre for manufacture of graphene and graphene-oxide doped fibre reinforced thermoset polymer composites.

Short-term goals

- Investigate individual properties of 2D materials
- Tight collaboration between partners across Chalmers
- Develop a value chain across Chalmers, from graphene synthesis, to small and then large-scale processing, characterization, and engineering/testing of materials for different applications

Long-term goals

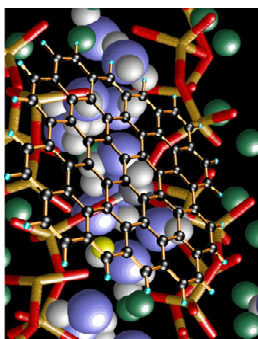
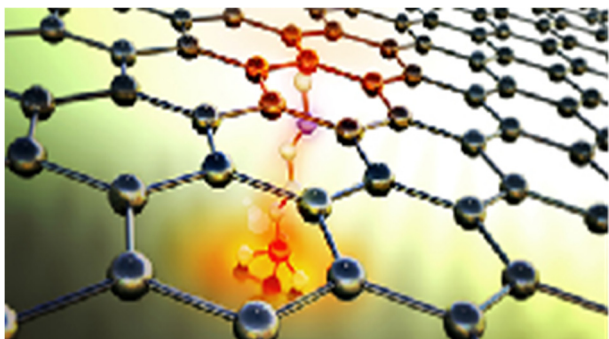
Explore high-level structures with combinations of these properties:

- Expansion of research in multifunctional composites for electronics and thermoelectrical applications (electronics packaging, nanoscale heat transfer, advanced energy materials) and for durability and manufacturability for polymer, metal, cement materials,
- Functional 2D materials for composites based on multiferroic and ferroelectric thin films and for impact resilience,
- Microtechnology fabrication and processing methods for thin composite films,
- Development of carbon nano- and 2D materials for 3D electronics packaging,
- Synthesis and processing of CNTs, graphene and related 2D materials for thermal management and interconnect applications,
- Processing method development of vertical stacking CNT TSV technology, CNT/graphene assisted cooling technology, graphene heat spreader, high temperature stable conductive adhesives, nano-soldering, nano-thermal interface materials and biomedical nano-scaffolds,

- Use of nanotechnology and supramolecular chemistry to create new materials for mechanical, electronics and energy applications,
- Study of physical chemistry of organic semiconductors, polymer blends and composites and development of new plastic materials for energy harvesting, storage and transport technologies (organic solar cells, thermoelectrics and power cables),
- Graphene based materials as a plastic additive that allows the modulation of thermal and electrical conductivity as well as mechanical properties,
- Recycling of plastics that contain graphene based additives,
- Optimization of polymer matrix composite processing techniques,
- Improvement of continuum and material mechanics with emphasis on modelling and simulation of nanoscale deformation, such as crack propagation, using numerical methods in computational material and failure mechanics,
- Advancement of processing methods for powder metallurgy & high strength materials,
- Examination of the relationship between the rheological properties and the linear and nonlinear flow dynamics of complex materials to understand the interplay between their molecular structure, processing and performance,
- Advanced multiscale modelling of GRM flake dispersions and their rheology to aid development & optimization of designs for scalable materials fabrication and processing,
- Investigation of cementitious materials and products with nanoscale additives, focusing on the durability and aging of materials.

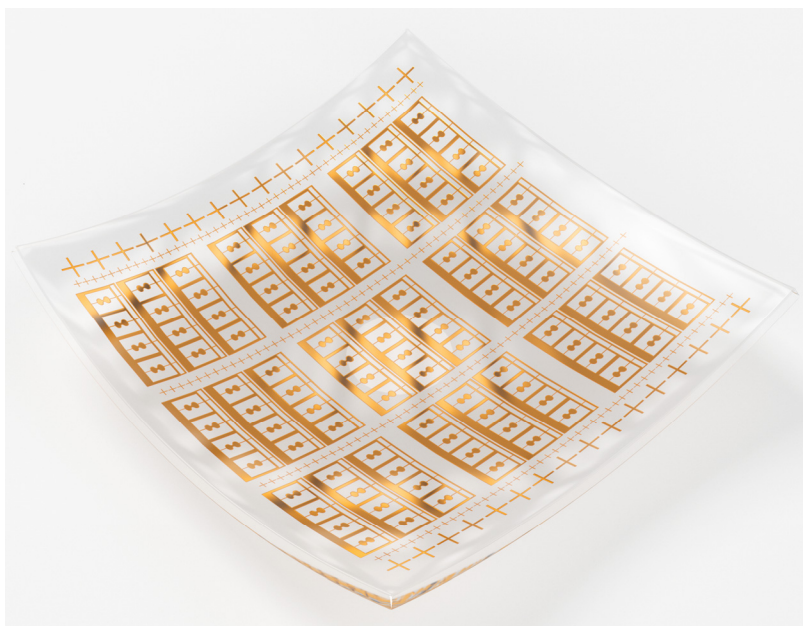
In summary, the primary goals are to increase mechanical, electrical and thermal properties and to decrease the weight. The end use concepts are:

- Heated Floor Materials - foldable thermal materials,
- Lightweight heat exchanger - computer and electronics,
- Functional paper - printed electronics,
- Micro lattice - coated lightweight sandwich core materials,
- Thermally and electrically conducting thermoplastic composites for power cables.



Examples of chemical functionalization of graphene and how it can facilitate thermal transport and increase the strength of cement-based concrete [J. Liu, L. Tang].

FOCUS AREA – ELECTRONICS AND PHOTONICS



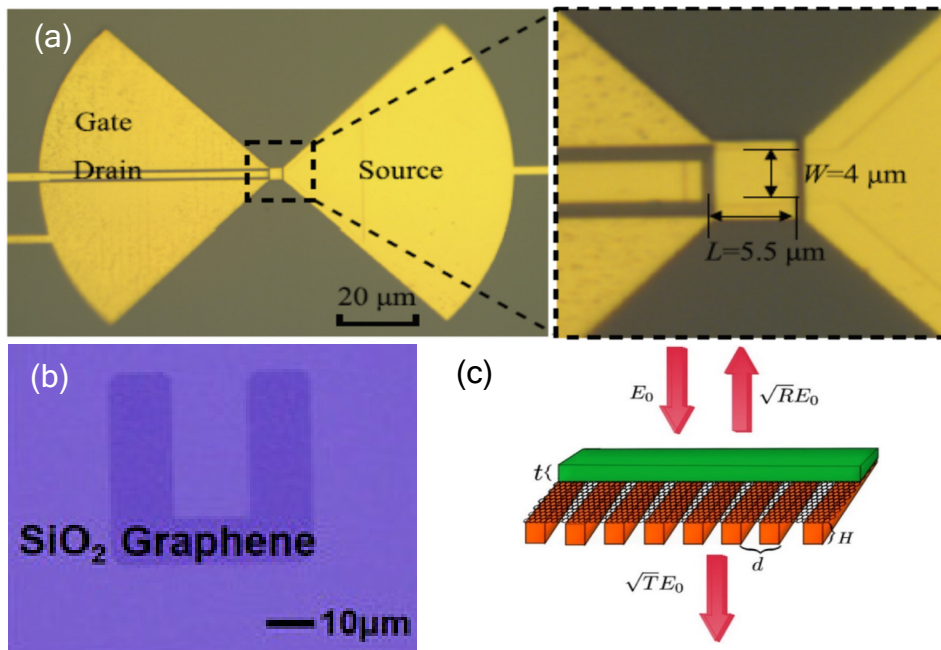
The first mechanically flexible detector for terahertz frequencies based on graphene
[X. Yang, A. Vorobiev, A. Generalov, M. A. Andersson and J. Stake].

Present Status

The research activities at Chalmers regarding electronics and photonics based on graphene and related 2D materials include materials growth and transfer of CVD graphene, growth of other 2D materials, development of graphene-based devices, graphene interconnects, graphene plasmonics, modelling of transport, optics, and carrier dynamics in graphene and related 2D materials.

In the field of materials' growth, the research activities focus on CVD graphene, graphene transfer by electrochemical bubbling, growth of new 2D materials and transfer, and bio- or environment-monitoring sensors from CVD graphene (Jie Sun, Avgust Yurgens). Concerning the area of electronics, the activities focus on graphene-based devices for mm-wave and terahertz applications (Jan Stake, Omid Habibpour, Andrei Vorobiev), vertical and horizontal graphene interconnects (Johan Liu, Yifeng Fu), quantum transport theory of charge, spin, and heat in graphene (Tomas Löfwander), high-speed electronic circuit design for communication and sensors (Herbert Zirath, Omid Habibpour), electronic charge, spin and quantum transport in 2D materials and related heterostructures (Saroj Dash), and epitaxial graphene growth and devices (Sergey Kubatkin, Samuel Lara Avila). In the field of photonics, Chalmers research activities include quantum transport theory in strongly correlated electron systems based on non-equilibrium many body theory (Mikael Fogelström), computational modelling of nanophotonic structures at terahertz frequencies including graphene plasmonics (Philippe Tassin), and microscopic modelling of carrier dynamics in graphene

and exciton dynamics in transition metal dichalcogenides (Ermin Malic). The activities also include experimental investigations of structural properties using high-resolution microscopy (Eva Olsson), optical spectroscopy of atomically thin 2D semiconductors and their interactions with plasmonic nanostructures (Timur Shegai), ferroelectric liquid crystals on graphene (Per Rudquist), and plasmonics of graphene-metal nanoparticle heterostructures for gas sensing (Christoph Langhammer). Valuable infrastructure resources are available at the Nanofabrication Laboratory (NFL) at MC2, the Centre for scientific and technical computing at the Physics department (C3SE) and Chalmers' Materials Analysis Laboratory (CMAL).



(a) Recent realization at Chalmers of a flexible terahertz electronics detector.
 (b) The growth and precise patterning of graphene is an important challenge for realizing electronic and photonic components with graphene.
 (c) Graphene plasmons can be used for highly sensitive refractive index sensing [J. Sun, J. Stake, P. Tassin].

Strengths and Challenges

The electronics and photonics-related groups at Chalmers have developed strong expertise and are internationally recognized in several fields. The groups are surrounded by good facilities (e.g. nanofabrication laboratory) and have a strong connection with the EU Flagship and with FlagEra projects. The main challenges are gaps in infrastructure (e.g., graphene high temperature treatment furnace, high-RAM high-performance computing equipment, equipment for growth and assembly of other 2D materials and Van der Waals heterostructures, evaporation systems, infrastructure for electrical characterization in sub-K temperatures, surface characterization equipment, graphene ink-jet printer). For many applications, the uniformity of graphene is currently insufficient, so a major challenge is the development of more uniform graphene samples. There is in general also a lack of long-term funding for personnel.

Short-term goals

Concerning the growth of materials, the following goals have been identified:

- van der Waals growth of 2D materials such as 2D semiconductors and topological insulators on graphene and h-BN
- Industry-grade production of epitaxial graphene
- Regarding electronics devices the following goals will be addressed:
- High-frequency electronics on graphene and THz components (e.g., detectors),
- Ultra-linear resistive mixers at W-band (70-110 GHz) and D-band (140-170GHz),
- Drain current saturation in GFETs via charge carrier velocity saturation in high fields with the aim to overcome the zero-bandgap limitation & improve transistor power gain,
- Development of hBN encapsulated GFETs with significantly improved performance for applications in mm-wave and THz amplifiers, frequency mixers, power detectors, etc.,
- Flexible arrays of GFET THz detectors for imaging and communication,
- Application of graphene interconnects to electronics and power devices.

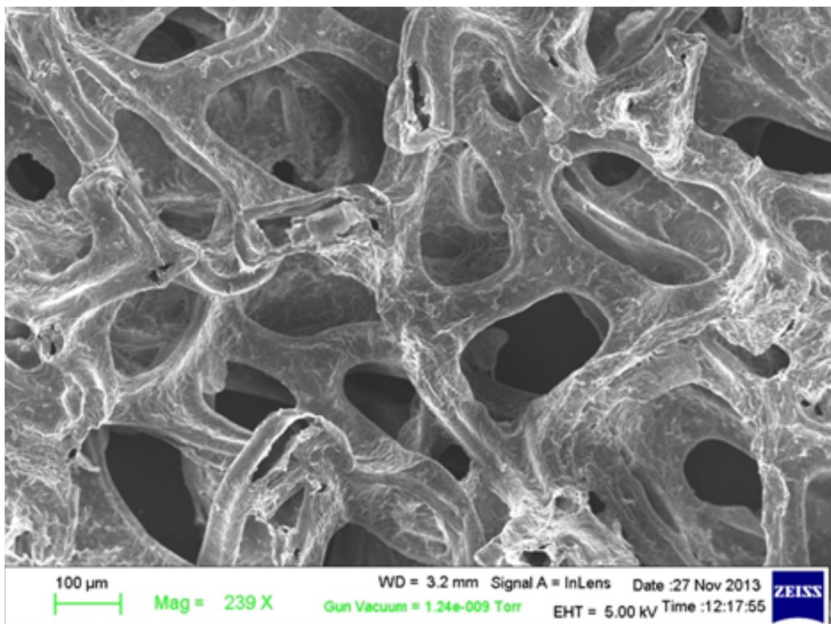
In the area of photonics, we target at the following goals:

- Multispectral detectors at mid-IR,
- Tunable nanophotonic structures,
- Graphene plasmonic devices,
- Exploiting dark exciton phenomena for novel sensing technologies,
- Sensors with 2D materials other than graphene (e.g., phosphorene),
- Application of graphene interconnects to LEDs.

Long-term goals

- Establish a consistent approach involving density matrix and density functional theory with the ability to model photodetecting, photoemitting and photoamplifying devices, reliable technology for scaling up fabrication of sensors, mixers and detectors,
- Growth of epitaxial graphene as a commercial technology alternative (electronics & optoelectronics),
- Large area growth of van der Waals heterostructures,
- Plasmonic devices controlled by low-frequency currents (bridge between electronics and photonics),
- Application of 2D materials beyond graphene to electronics, optoelectronics, spintronics and quantum technology,
- Development of state-of-the-art and novel mm-wave and THz graphene based electronic devices and finding a niche for their commercialization,
- Use of graphene for interconnect and thermal management of electronics in large scale.

FOCUS AREA – ENERGY APPLICATIONS



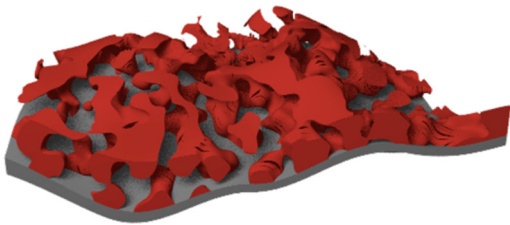
Porous graphene foam coated by nanocrystalline Fe_2O_3 for Li batteries [V. Palermo].

Present status

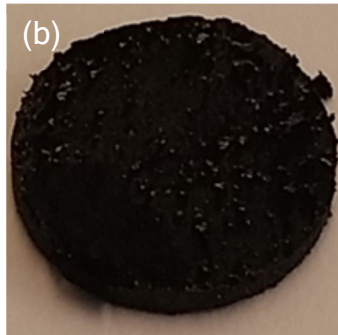
There are several research activities at Chalmers in the field of energy applications involving graphene, covering the whole chain from fabrication of required raw material to its use in devices. The main activities include production of CVD graphene of varying morphology (Jie Sun), composite, film and scaffold materials (Roland Kadár, Yifeng Fu, Johan Liu), structure, properties and synthesis correlation using high-resolution microscopy and in situ studies (Eva Olsson), thermal management (Yifeng Fu, Johan Liu), catalysis and photocatalysis, solar and fuel cells (Dinko Chakarov, Ergang Wang), and batteries (Aleksandar Matic, Patrik Johansson, Vincenzo Palermo). The research activities currently addressed focus on solar cells, batteries (photocatalysis), thermal management, LEDs and microbial fuel cells (Ivan Mijakovic). The latter is an area of research focusing on the production of energy from biomass and overlapping with the focus area of bio applications).

The research is conducted at different laboratories/groups supported by open access facilities, such as the Nanofabrication Laboratory (NFL) at MC2, the Centre for scientific and technical computing at Chalmers (C3SE) and Chalmers Materials Analysis Laboratory (CMAL). Several other facilities are also available to the researchers (absorption optical spectrophotometry, chemical photo-reactors and waste-water characterization, Dinko Chakarov), and others are being created from scratch (e.g. Solar-cell Lab, Ergang Wang). Thermal management solutions based on graphene are developed and tested at the Electronics Materials and Systems Laboratory at MC2 with transient- and steady-state measurement tools for a wide range of materials and structures. Graphene in battery devices can be tested at the battery research laboratory at the department of Physics. Microbial fuel cell applications are also tested at the Department of Architecture and Civil Engineering where reactors setups are available.

(a)



(b)



(a) Schematic of porous graphene foam coated by nanocrystalline Fe_2O_3 for Li batteries [V. Palermo]
 (b) Highly conductive graphene aerogel as a cathode [A. Matic]

Strengths and challenges

The strength of this field relies in the synergetic combination of strong researchers and available infrastructure and the anticipation of the strategic impact of this focus area addressing vital societal challenges such as a sustainable production and efficient management of energy, which are top priority for the UN, the EU and the Swedish government. Its intrinsic importance stems from the unresolved issues related to the rapid growth of the world population. The main challenges that need to be addressed are to demonstrate real-world competitiveness of graphene-based devices and technologies and to mobilize collaborations within Chalmers in an efficient and rewarding way. We envision graphene to enter many everyday life applications. For that, the first step is to develop functional prototypes (short-term), which will be developed and commercialized in collaboration with strategic stakeholders (long-term).

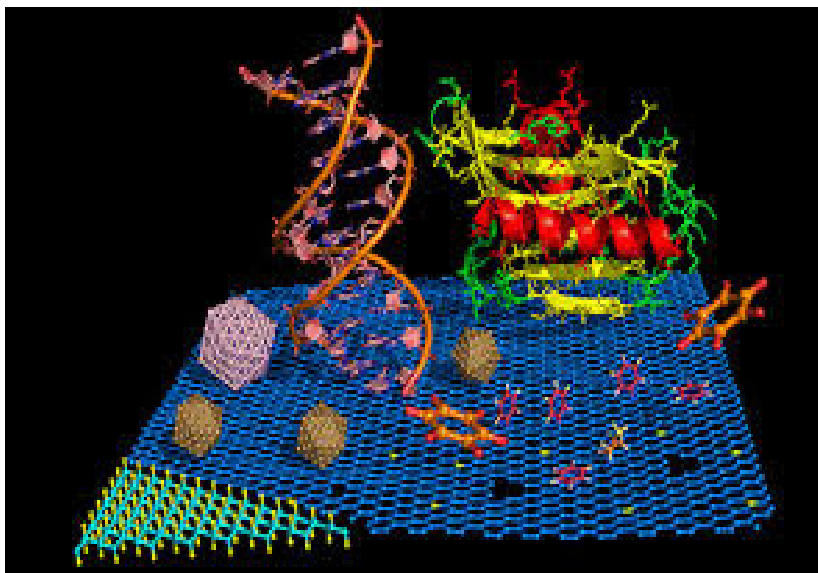
Short-term goals

- Prototypes of graphene-integrated solar cell panels, LED's, and supercapacitors,
- Developing graphene based technology in thermal management for LED's and batteries,
- Using graphene as self-standing Li-S battery electrodes and as scaffolds for organic Al metal batteries,
- Understanding the effects of vertical graphene electrodes in microbial fuel cells.

Long-term goals

- Commercialization of large-area printed solar cells based on graphene-like materials,
- Use of graphene for improved current density batteries for faster re-charging and to enable use of novel organic redox active materials,
- Graphene composite materials used in conducting transparent electrodes in solar cells and LED's,
- Use of graphene in cooling of electronics and other power devices,
- Understand fundamentals of how to achieve high thermal conductivity in graphene structures.

FOCUS AREA – BIO APPLICATIONS



Optimal surface-to-volume ratio of 2D materials is promising for efficient bio sensors.
[free-stock-illustration].

Present status

The area of bio applications is still in its developing stage and taking advantage of the promising applications of graphene and 2D materials in applications such as biosensors, antibacterial coatings and other very interesting applications. The main activities in this area include production of CVD graphene of varying morphology (J. Sun), modelling and functionalization of graphene of various kinds (Itai Panas, Valentina Cantatore, Severin Schindler, Siegfried Eigler), structure, properties and synthesis correlation using high-resolution microscopy and in situ studies (Eva Olsson), life-cycle and environmental risk assessment (Rickard Arvidsson), antibacterial surfaces (Ivan Mijakovic, Jie Sun, Roland Kadár) biosensors (Ivan Mijakovic, Avgust Yurgens, Itai Panas, Valentina Cantatore), extraction of products from cell factories and microbial fuel cells (Dina Petranovic, Ivan Mijakovic).

Strengths and challenges

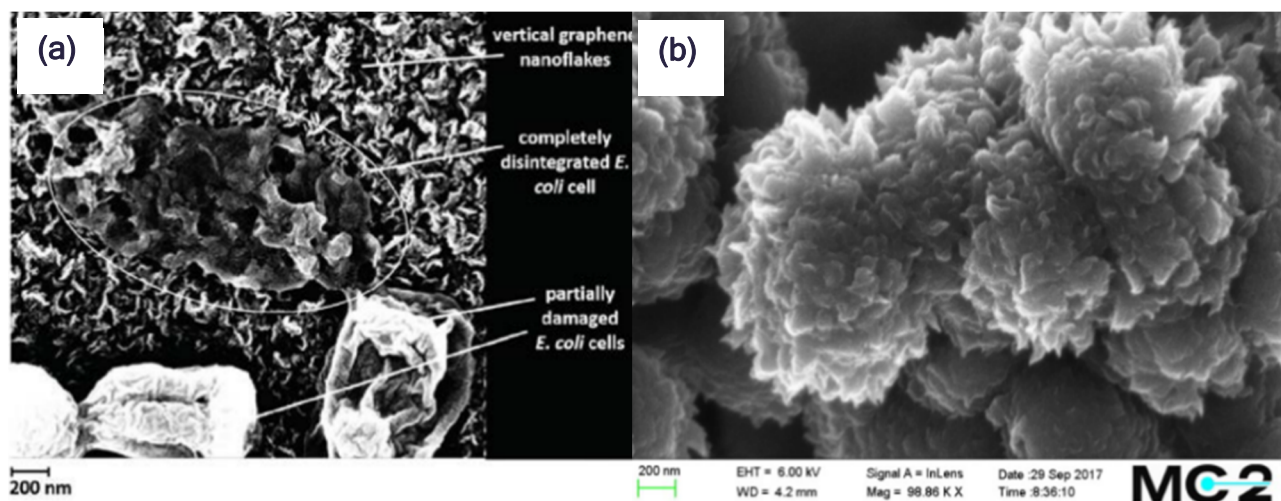
The strength of this focus area is the enormous potential of strategic impact by addressing important societal challenges such as the development of new pharmaceuticals and the engineering of advanced solutions for personalized medicines. Improved healthcare is a top priority for both the UN and the EU, including the Swedish government, and its importance stems from the unresolved issues related to rapid growth of the human population and increased life span (aging population). Biosensors can for example be used for assessing freshness of packaged food and thereby avoiding food poisoning. The main challenge that must be addressed is to resolve questions on graphene biocompatibility and safety in different settings/devices.

Short-term goals

- Demonstrator of graphene biosensor with enhanced selectivity,
- Understanding the effects of vertical graphene electrodes in microbial fuel cells,
- Demonstrate efficient extraction of lipids and proteins from microbial cell factories,
- Safety and biocompatibility assessed for all demonstrators/prototypes.

Long-term goals

- Production of graphene-based biosensors and their commercialization for use in medical devices and hospitals, food production, detection of environmental pollution, etc.,
- Graphene-enhanced microbial fuel cells for treatment and resource recovery from wastewater,
- Graphene-based extraction of lipids and proteins implemented in industrial fermentation processes,
- Our data on safety and biocompatibility integrated in legislation for safe use of graphene.



(a) Vertically aligned graphene coating on a SiO₂ surface kills bacteria; (b) the same on iron nanoparticles can be used for lipid extraction [I. Mijakovic].

REQUIERED FUTURE STEPS

Research development

The following research areas need to be strengthened at Chalmers:

- Interlayer phenomena in heterostructures including electrical, excitonic, spintronic, optical, superconducting, magnetic and topological quantum effects (fundamentals),
- Multifunctional composites for electronics and thermoelectrical applications for electronics packaging, nanoscale heat transfer and advanced energy materials (composites and coatings),
- 2D materials beyond graphene for electronics, optoelectronics, spintronics and quantum technology (electronics and photonics),
- Improved current density batteries for faster re-charging and improved cooling of electronics devices (energy applications),
- Selective and sensitive biosensors and graphene biocompatibility (bio applications).

Infrastructure

The following infrastructure is needed in order to be competitive in the field of 2D materials:

- Facilities to grow 2D materials beyond graphene, such as semiconductors and other 2D layered quantum materials and their heterostructures,
- Infrastructure for low-temperature magneto and quantum transport measurements
- Ultra-fast pump-probe measurements,
- Dedicated electron beam evaporator with ultra-high vacuum and annealing systems,
- Graphene high-temperature-treatment furnace up to 3200 °C that offer vacuum pumping, gas refilling and quick heating properties based on induction heating. It is extremely important that we can control the properties of graphene in terms of grain size and impurity control. This is one of the most important ways to get large scale graphene flakes and films with extremely high quality (oxygen, ionic content etc),
- High-RAM high-performance computing equipment,
- Surface characterization equipment, such as XPS, LEED, LEEM, ARPES,
- Graphene ink-jet printer.

INTERNAL ADVISORY AND STEERING BOARD

Internal Advisory Board

- Saroj Dash, Thomas Löfwander (Fundamentals)
- Brina Blinzler, Vincenzo Palermo (Multifunctional Composites and coatings)
- Philippe Tassin, Jan Stake (Electronics and Photonics)
- Avgust Yurgens, Ivan Mijakovic (Bio and energy applications)

Steering Board

- Aleksandar Matic (Director of the Area of Advance Materials)
- Bo Albinsson (Director of the Excellence Initiative Nano)
- Mikael Fogelström (Head of the Dept. of Microtechnology and Nanoscience - MC2)
- Leif Åhman (Head of Department of Chemistry)
- Avgust Yurgens (Director of the Graphene Innovation Lab)
- Cristina Andersson (GCC, Coordinator of Industrial Relations)
- Ermin Malic (GCC Director)

We would like to thank the Internal Advisory Board members for their valuable input to this roadmap. We also would like to thank Susannah Carlsson for proofreading the document.

RESEARCHERS

	FOCUS AREAS				
	Fundamentals	Multifunctional Composites and Coatings	Electronics and Photonics	Energy applications	Bio applications
Aleksandar Matic					
Anders Palmqvist					
Andreas Isacsson					
Andrei Vorobiev					
Av gust Yurgens					
Brina Blinzler					
Christian Muller					
Christoph Langhammer					
Dina Petranovic Nielsen					
Dinko Chakarov					
Elsebeth Schröder					
Ergang Wang					
Ermin Malic					
Eva Olsson					
Floriana Lombardi					
Herbert Zirath					
Itai Panas					
Ivan Mijakovic					
Jan Stake					
Jari Kinaret					
Jie Sun					
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Leif Asp					
Luping Tang					
Mikael Fogelström					
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Paul Erhart					
Per Hyldgaard					
Per Rudquist					
Philippe Tassin					
Ragnar Larsson					
Rickard Arvidsson					
Roland Kádár					
Samuel Lara Avila					
Saroj Dash					
Sergey Kubatkin					
Severin Schindler					
Siegfried Eigler					
Thilo Bauch					
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Learn more about the
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