Oxidation of Suspended Graphene: Etch Dynamics and Stability Beyond 1000 °C

We study the oxidation of clean suspended mono- and few-layer graphene in real-time by in situ environmental transmission electron microscopy. At an oxygen pressure below 0.1 mbar we observe anisotropic oxidation in which armchair-oriented hexagonal holes are formed with a sharp edge roughness below 1 nm. At a higher pressure, we observe an increasingly isotropic oxidation, eventually leading to irregular holes at a pressure of 6 mbar. In addition, we find that few-layer flakes are stable against oxidation at temperatures up to at least 1000 °C in the absence of impurities and electron beam-induced defects. These findings show first that the oxidation behavior of mono- and few-layer graphene depends critically on the intrinsic roughness, cleanliness and any imposed roughness or additional reactivity from a supporting substrate; and second, the activation energy for oxidation of pristine suspended few-layer graphene is up to 43 % higher than previously reported for graphite. In addition we have developed a cleaning scheme that results in the near complete removal of hydrocarbon residues over the entire visible sample area. These results have implications for applications of graphene where edge roughness can critically affect the performance of devices, and more generally highlights the surprising (meta)stability of the basal plane of suspended bilayer and thicker graphene towards oxidative environments at high temperature.
We use confocal Raman microscopy and a recently proposed vector analysis scheme to investigate the nanoscale origin of strain and carrier concentration in exfoliated graphene-hexagonal boron nitride (hBN) heterostructures on silicon dioxide (SiO$_2$). Two types of heterostructures are studied: graphene on SiO$_2$ partially covered by hBN, and graphene fully encapsulated between two hBN flakes. We extend the vector analysis method to produce separated spatial maps of the strain and doping variation across the heterostructures. This allows us to visualise and directly quantify the much-speculated effect of the environment on carrier concentration in graphene. Moreover, we demonstrate that variations in strain and carrier concentration in graphene arise from nanoscale features of the heterostructures such as fractures, folds and bubbles trapped between layers. For bubbles in hBN-encapsulated graphene, hydrostatic strain is shown to be greatest at bubble centres, whereas the maximum carrier concentration is localised at bubble edges. Raman spectroscopy is shown to be a non-invasive tool for probing strain and doping in graphene, which could prove useful for engineering of two-dimensional devices.

General information
State: Published
A Graphene-Edge Ferroelectric Molecular Switch

We show that polar molecules (water, ammonia, and nitrogen dioxide) adsorbed solely at the exposed edges of an encapsulated graphene sheet exhibit ferroelectricity, collectively orienting and switching reproducibly between two available states in response to an external electric field. This ferroelectric molecular switching introduces drastic modifications to the graphene bulk conductivity and produces a large and ambipolar charge bistability in micrometer-size graphene devices. This system comprises an experimental realization of envisioned memory capacitive ("memcapacitive") devices whose capacitance is a function of their charging history, here conceived via confined and correlated polar molecules at the one-dimensional edge of a two-dimensional crystal.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene, Theoretical Nanoelectronics, Technical University of Denmark, Politecnico University of Milan
Contributors: Caridad, J. M., Calogero, G., Pedrinazzi, P., Santos, J. E. V. D. S. M., Impellizzeri, A., Gunst, T., Booth, T. J., Sordan, R., Bøggild, P., Brandbyge, M.
Number of pages: 9
Pages: 4675-4683
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Nano Letters
Keywords: Graphene edges, Polar molecules, Ferroelectricity, Mqemcapacitor, Hysteresis, Molecular switch
Colorimetric sensing of dopamine using hexagonal silver nanoparticles decorated by task-specific pyridinium based ionic liquid

A simple and sensitive platform was introduced for detection of dopamine (DA) based on morphology transition and etching strategy of hexagonal platelet shaped silver nanoparticles (Ag NPs) functionalized with task-specific ionic liquid (TSIL). In this study, a pyridinium based TSIL was used for surface functionalization. According to the etching strategy, hexagonal TSIL-Ag NPs were converted to round-shape nanoparticles in the presence of DA. This etching process caused a blue shift in the localized surface plasmon resonance (LSPR) peak of TSIL-Ag NPs. The maximum absorption band shifted from 585 nm to 500 nm. Color change from green to red was also observed as a consequence of morphology transition of TSIL-Ag NPs. The color change and change in the $A_{500}/A_{585}$ ratio versus DA concentration were linear in the range of $0.1\text{–}7.5 \mu$M with a detection limit of $0.031 \mu$M. Moreover, the developed approach was applied for detection and determination of DA in human serum sample. This simple, rapid and selective method provided a promising sensing probe for detection of DA in biological fluids.

**General information**

State: Published
Organisations: Center for Nanostructured Graphene, Department of Micro- and Nanotechnology, Nanocarbon, K.N. Toosi University of Technology, Iranian National Institute for Oceanography and Atmospheric Science, Amirkabir University of Technology
Contributors: Rostami, S., Mehdinia, A., Jabbari, A., Kowsari, E., Niroumand, R., Booth, T. J.
Pages: 64-72
Publication date: 2018
Peer-reviewed: Yes

**Publication information**

Journal: Sensors and Actuators B: Chemical
Volume: 271
ISSN (Print): 0925-4005
Ratings:
- BFI (2019): BFI-level 2
- Web of Science (2019): Indexed yes
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 1
- Scopus rating (2017): CiteScore 5.67 SJR 1.406 SNIP 1.453
- Web of Science (2017): Impact factor 5.667
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 1
- Scopus rating (2016): CiteScore 5.07 SJR 1.343 SNIP 1.464
- Web of Science (2016): Impact factor 5.401
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 1
- Scopus rating (2015): CiteScore 4.84 SJR 1.225 SNIP 1.484
- Web of Science (2015): Impact factor 4.758
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 1
- Scopus rating (2014): CiteScore 4.37 SJR 1.229 SNIP 1.658
- Web of Science (2014): Impact factor 4.097
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 1
- Scopus rating (2013): CiteScore 4.25 SJR 1.261 SNIP 1.638
- Web of Science (2013): Impact factor 3.84
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
Conductance quantization suppression in the quantum Hall regime

Conductance quantization is the quintessential feature of electronic transport in non-interacting mesoscopic systems. This phenomenon is observed in quasi one-dimensional conductors at zero magnetic field $B$, and the formation of edge states at finite magnetic fields results in wider conductance plateaus within the quantum Hall regime. Electrostatic interactions can change this picture qualitatively. At finite $B$, screening mechanisms in narrow, gated ballistic conductors are predicted to give rise to an increase in conductance and a suppression of quantization due to the appearance of additional conduction channels. Despite being a universal effect, this regime has proven experimentally elusive because of difficulties in realizing one-dimensional systems with sufficiently hard-walled, disorder-free confinement. Here, we experimentally demonstrate the suppression of conductance quantization within the quantum Hall regime for graphene nanoconstrictions with low edge roughness. Our findings may have profound impact on fundamental studies of quantum transport in finite-size, two-dimensional crystals with low disorder.

General information
State: Published
High-quality graphene flakes exfoliated on a flat hydrophobic polymer

We show that graphene supported on a hydrophobic and flat polymer surface results in flakes with extremely low doping and strain as assessed by their Raman spectroscopic characteristics. We exemplify this technique by micromechanical exfoliation of graphene on flat poly(methylmethacrylate) layers and demonstrate Raman peak intensity ratios I(2D)/I(G) approaching 10, similar to pristine freestanding graphene. We verify that these features are not an artifact of optical interference effects occurring at the substrate: they are similarly observed when varying the substrate thickness and are maintained when the environment of the graphene flake is completely changed, by encapsulating preselected flakes between hexagonal boron nitride layers. The exfoliation of clean, pristine graphene layers directly on flat polymer substrates enables high performance, supported, and non-encapsulated graphene devices for flexible and transparent optoelectronic studies. We additionally show that the access to a clean and supported graphene source leads to high-quality van der Waals heterostructures and devices with reproducible carrier mobilities exceeding 50 000 cm² V⁻¹ s⁻¹ at room temperature.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene, Technical University of Denmark, Polytechnic University of Milan
Number of pages: 5
Publication date: 2018
Peer-reviewed: Yes

Publication information
Volume: 112
Issue number: 3
Article number: 033101
ISSN (Print): 0003-6951
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.25 SJR 1.382 SNIP 1.167
Web of Science (2017): Impact factor 3.495
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.67 SJR 1.673 SNIP 1.249
Web of Science (2016): Impact factor 3.411
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 2.47 SJR 1.499 SNIP 1.226
Web of Science (2015): Impact factor 3.142
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.25 SJR 1.861 SNIP 1.492
Web of Science (2014): Impact factor 3.302
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.77 SJR 2.146 SNIP 1.633
Web of Science (2013): Impact factor 3.515
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.76 SJR 2.57 SNIP 1.739
Quantitative optical mapping of two-dimensional materials

The pace of two-dimensional materials (2DM) research has been greatly accelerated by the ability to identify exfoliated thicknesses down to a monolayer from their optical contrast. Since this process requires time-consuming and error-prone manual assignment to avoid false-positives from image features with similar contrast, efforts towards fast and reliable automated assignments schemes is essential. We show that by modelling the expected 2DM contrast in digitally captured images, we can automatically identify candidate regions of 2DM. More importantly, we show a computationally-light machine vision strategy for eliminating false-positives from this set of 2DM candidates through the combined use of binary thresholding, opening and closing filters, and shape-analysis from edge detection. Calculation of data pyramids for arbitrarily high-resolution optical coverage maps of two-dimensional materials produced in this way allows the real-time presentation and processing of this image data in a zoomable interface, enabling large datasets to be explored and analysed with ease. The result is that a standard optical microscope with CCD camera can be used as an analysis tool
able to accurately determine the coverage, residue/contamination concentration, and layer number for a wide range of presented 2DMs.

**General information**

State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene
Contributors: Jessen, B. S., Whelan, P. R., Mackenzie, D. M. A., Luo, B., Thomsen, J. D., Gammelgaard, L., Booth, T. J., Bøggild, P.
Number of pages: 8
Publication date: 2018
Peer-reviewed: Yes

**Publication information**

Journal: Scientific Reports
Volume: 8
Issue number: 1
Article number: 6381
ISSN (Print): 2045-2322
Ratings:

- BFI (2019): BFI-level 1
- Web of Science (2019): Indexed yes
- BFI (2018): BFI-level 1
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 1
- Scopus rating (2017): CiteScore 4.36 SJR 1.533 SNIP 1.245
- Web of Science (2017): Impact factor 4.122
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 1
- Scopus rating (2016): CiteScore 4.63 SJR 1.692 SNIP 1.354
- Web of Science (2016): Impact factor 4.259
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 1
  - Scopus rating (2015): CiteScore 5.3 SJR 2.034 SNIP 1.597
  - Web of Science (2015): Impact factor 5.228
  - Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 1
  - Scopus rating (2014): CiteScore 4.75 SJR 2.163 SNIP 1.554
  - Web of Science (2014): Impact factor 5.578
  - Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 1
  - Scopus rating (2013): CiteScore 4.06 SJR 1.998 SNIP 1.57
  - Web of Science (2013): Impact factor 5.078
  - ISI indexed (2013): ISI indexed yes
  - Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 1
  - Scopus rating (2012): CiteScore 2.44 SJR 1.531 SNIP 0.962
  - Web of Science (2012): Impact factor 2.927
  - ISI indexed (2012): ISI indexed yes
  - Web of Science (2012): Indexed yes
  - Web of Science (2011): Impact factor
  - ISI indexed (2011): ISI indexed no
Original language: English
Electronic versions:
Untitled.pdf
DOIs:
10.1038/s41598-018-23922-1
Source: FindIt
Source-ID: 2418789264
Differences in inflammation and acute phase response but similar genotoxicity in mice following pulmonary exposure to graphene oxide and reduced graphene oxide

We investigated toxicity of 2-3 layered >1 μm sized graphene oxide (GO) and reduced graphene oxide (rGO) in mice following single intratracheal exposure with respect to pulmonary inflammation, acute phase response (biomarker for risk of cardiovascular disease) and genotoxicity. In addition, we assessed exposure levels of particulate matter emitted during production of graphene in a clean room and in a normal industrial environment using chemical vapour deposition. Toxicity was evaluated at day 1, 3, 28 and 90 days (18, 54 and 162 µg/mouse), except for GO exposed mice at day 28 and 90 where only the lowest dose was evaluated. GO induced a strong acute inflammatory response together with a pulmonary (Serum-Amyloid A, Saa3) and hepatic (Saa1) acute phase response. rGO induced less acute, but a constant and prolonged inflammation up to day 90. Lung histopathology showed particle agglomerates at day 90 without signs of fibrosis. In addition, DNA damage in BAL cells was observed across time points and doses for both GO and rGO. In conclusion, pulmonary exposure to GO and rGO induced inflammation, acute phase response and genotoxicity but no fibrosis.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, National Research Centre for the Working Environment, Roskilde University, National Institute of Occupational Health, Graphenea
Number of pages: 25
Pages: e0178355
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: P L o S One
Volume: 12
Issue number: 6
ISSN (Print): 1932-6203
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 3.01 SJR 1.164 SNIP 1.111
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 3.11 SJR 1.236 SNIP 1.101
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 3.32 SJR 1.427 SNIP 1.136
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 3.54 SJR 1.559 SNIP 1.148
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 3.94 SJR 1.772 SNIP 1.153
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 4.15 SJR 1.982 SNIP 1.156
Web of Science (2012): Impact factor 3.73
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
Large-scale Fabrication of 2D Materials by Chemical Vapor Deposition

The family of 2D materials comprises a vast range of few-atom thick materials held together by van der Waals interactions that have a diverse set of material properties. While these materials are interesting in their own right, the most exciting aspect of their research is the ability to combine this vast range of materials - without the lattice mismatch constraints of conventional 3D materials - into atomically engineered, artificial 3D crystals that pave the way for new physics, and subsequently, for new applications. 2D materials are expected to disrupt a number of industries in the future, such as electronics, displays, energy, and catalysis. The key bottleneck for commercial implementation is in large-scale synthesis and subsequent fabrication of high quality devices. Chemical vapor deposition is considered to be the most economically feasible synthesis method to this end. In the case of graphene, for which synthesis and transfer methods have been established, the key bottleneck is in cost reduction and device integration without significant degradation of material properties. In the case of the other 2D materials, the key bottleneck is in the absence of reliable and scalable methods for synthesis.

This thesis aims to address some of the challenges associated with materials fabrication in order to lay the groundwork for commercial implementation of 2D materials. To improve graphene implementation in electronic applications, copper catalyst foils were engineered to reduce surface roughness, wrinkles, and polycrystallinity in the resulting graphene layer; in the process, monocrystalline copper foils with a post-process surface roughness below 10 nm - an order of magnitude lower than current commercial foils - were achieved. A new transfer technique was also developed as a route towards vertical integration of device fabrication process steps.

To realize large-scale and economical graphene production, significant reductions in graphene production cost were achieved through efficient space utilization in a commercial chemical vapor deposition reactor, allowing for a 30x improvement in throughput. A large-scale, non-destructive transfer process for DIY-application of graphene films onto arbitrary substrates was also developed through the use of commercially available polymer films and solvents. Finally, a novel in-situ process monitoring tool was developed to complement large-scale graphene production, which was used here to troubleshoot and optimize processes to enable reproducible and high quality graphene synthesis.

To address the challenge of synthesizing the vast library of 2D materials, a universal platform for 2D materials synthesis via CVD-like conditions was invented, and was used to synthesize more than 26 different compounds - some well-known and others never-before isolated - to demonstrate its universality. The discovery of this general growth method calls for a perspective shift from the conventional 2D materials growth model inherited from graphene synthesis on copper, and provides an instructional guide for rapidly synthesizing prospective new 2D materials, paving the way for accelerated progress in the field in coming years.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon
Contributors: Shivayogimath, A., Bøggild, P., Booth, T.
Measuring and Tailoring the Structure of Two-Dimensional Materials by Transmission Electron Microscopy

As the critical dimensions of electronic devices decrease in size, the nanoscale structure becomes important for the electronic properties. Two-dimensional (2D) materials, with a thickness down to one atom, are very affected by disorder. Any type of disorder in graphene, including lattice disorder, roughness, and stress, contributes to charge carrier scattering and limits the carrier mobility. The current de-facto standard for making high quality graphene devices is by hexagonal boron nitride (hBN) encapsulation, which plays the role of a dielectric providing perfect protection from the environment and flattening the graphene. However, such encapsulated samples are commonly placed on silicon oxide substrates which are non-planar surfaces that induce roughness. Another source of carrier scattering, edge roughness, is detrimental for the carrier mobility of nanostructured graphene devices. The minimisation of these sources of scattering is, therefore, important for industrial applications as well as fundamental scientific purposes.

Transmission electron microscopy (TEM) is an excellent tool for structural characterisation of 2D materials because of its sub-angstrom resolution, and potential for adding stimuli like heat, electrical biasing, and studying the interaction with gas molecules. In this project, TEM has been used to measure the structure and also to physically pattern graphene on the nanoscale.

First, the design, fabrication and characterisation of TEM sample carriers for simultaneous in-situ heating and electrical biasing of 2D materials is presented. Chips with platinum heaters on a free-standing silicon nitride membrane were fabricated. The chips were capable of heating to 350 °C consistently for at least 24 hours, and displayed a maximum temperature of 749 °C. The best performing chips were found to be those with larger silicon nitride membranes, and the failure mechanism was related to the stability of the membranes. Patterning graphene with low edge roughness is necessary to avoid charge carrier mobility degradation in graphene devices. Crystallographic etching of graphene by oxygen is a viable route towards low edge roughness patterning and was investigated in an environmental TEM. The edge roughness was found to be dependent on the oxygen pressure, where lower pressures lead to hexagonally shaped holes in graphene with armchair-oriented edges, while higher pressures lead to irregularly shaped holes. Furthermore, the etch rate was found to increase with pressure, electron beam current density, and temperature. The high resolution of the TEM also allowed to study the discrete nature of the etching process at low pressures, where the instantaneous etch rates can be described by the Poisson distribution.

Finally, the roughness of suspended graphene, suspended graphene/hBN heterostructures, and hBN/graphene/hBN heterostructures were investigated by electron diffraction technique in the TEM. This method enables to measure the roughness of graphene at a higher resolution than scanning probe techniques, which suffer from noise at the low levels of roughness investigated here, and also measure the roughness of graphene embedded in hBN. The root mean square roughness of suspended bare graphene was measured to a value of 114 pm, and decreased to a value of 21 pm and 12 pm for hBN supported graphene and hBN encapsulated graphene, respectively. Simulations support the notion that hBN encapsulated graphene should display lower roughness than hBN supported graphene due to a localisation of flexural phonons in the hBN layers.
Probing the Gas-Phase Dynamics of Graphene Chemical Vapour Deposition using in-situ UV Absorption Spectroscopy

The processes governing multilayer nucleation in the chemical vapour deposition (CVD) of graphene are important for obtaining high-quality monolayer sheets, but remain poorly understood. Here we show that higher-order carbon species in the gas-phase play a major role in multilayer nucleation, through the use of in-situ ultraviolet (UV) absorption spectroscopy. These species are the volatilized products of reactions between hydrogen and carbon contaminants that have backstreamed into the reaction chamber from downstream system components. Consequently, we observe a dramatic suppression of multilayer nucleation when backstreaming is suppressed. These results point to an important and previously undescribed mechanism for multilayer nucleation, wherein higher-order gas-phase carbon species play an integral role. Our work highlights the importance of gas-phase dynamics in understanding the overall mechanism of graphene growth.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Experimental Surface and Nanomaterials Physics, Silicon Microtechnology, Center for Nanostructured Graphene
Contributors: Shivayogimath, A., Mackenzie, D., Luo, B., Hansen, O., Bøggild, P., Booth, T.
Number of pages: 10
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: Scientific Reports
Volume: 7
Issue number: 1
ISSN (Print): 2045-2322
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.36 SJR 1.533 SNIP 1.245
Web of Science (2017): Impact factor 4.122
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.63 SJR 1.692 SNIP 1.354
Web of Science (2016): Impact factor 4.259
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.3 SJR 2.034 SNIP 1.597
Web of Science (2015): Impact factor 5.228
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.75 SJR 2.163 SNIP 1.554
Web of Science (2014): Impact factor 5.578
Quality assessment of graphene: Continuity, uniformity, and accuracy of mobility measurements

With the increasing availability of large-area graphene, the ability to rapidly and accurately assess the quality of the electrical properties has become critically important. For practical applications, spatial variability in carrier density and carrier mobility must be controlled and minimized. We present a simple framework for assessing the quality and homogeneity of large-area graphene devices. The field effect in both exfoliated graphene devices encapsulated in hexagonal boron nitride and chemical vapor-deposited (CVD) devices was measured in dual current–voltage configurations and used to derive a single, gate-dependent effective shape factor, $\beta$, for each device. $\beta$ is a sensitive indicator of spatial homogeneity that can be obtained from samples of arbitrary shape. All 50 devices investigated in this study show a variation (up to tenfold) in $\beta$ as a function of the gate bias. Finite element simulations suggest that spatial doping inhomogeneity, rather than mobility inhomogeneity, is the primary cause of the gate dependence of $\beta$, and that measurable variations of $\beta$ can be caused by doping variations as small as $10^{10} \text{ cm}^{-2}$. Our results suggest that local variations in the position of the Dirac point alter the current flow and thus the effective sample shape as a function of the gate bias. We also found that such variations lead to systematic errors in carrier mobility calculations, which can be revealed by inspecting the corresponding $\beta$ factor.

General information

State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene
Number of pages: 10
Pages: 3596-3605
Publication date: 2017
Peer-reviewed: Yes

Publication Information
Journal: Nano Research
Volume: 10
Issue number: 10
ISSN (Print): 1998-0124
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 7.8 SJR 3.064 SNIP 1.394
Web of Science (2017): Impact factor 7.994
Raman spectral indicators of catalyst decoupling for transfer of CVD grown 2D materials

Through a combination of monitoring the Raman spectral characteristics of 2D materials grown on copper catalyst layers, and wafer scale automated detection of the fraction of transferred material, we reproducibly achieve transfers with over 97.5% monolayer hexagonal boron nitride and 99.7% monolayer graphene coverage, for up to 300 mm diameter wafers. We find a strong correlation between the transfer coverage obtained for graphene and the emergence of a lower wavenumber 2D peak component, with the concurrent disappearance of the higher wavenumber 2Dþ peak component during oxidation of the catalyst surface. The 2D peak characteristics can therefore act as an unambiguous predictor of the success of the transfer. The combined monitoring and transfer process presented here is highly scalable and amenable for roll-to-roll processing.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene, University of Cambridge, AIXTRON, Leibniz-Institut für Oberflächenmodifizierung e.V.
Pages: 75-81
Publication date: 2017
Peer-reviewed: Yes
Sputtering an exterior metal coating on copper enclosure for large-scale growth of single-crystalline graphene: Paper

We show the suppression of nucleation density in chemical vapor deposited graphene through the use of a sputtered metal coating on the exterior of a copper catalyst enclosure, resulting in the growth of sub-centimeter scale single crystal graphene domains and complete elimination of multilayer growth. The sputtered coating suppresses nucleation density by acting as both a diffusion barrier and as a sink for excess carbon during the growth, reducing the carbon concentration in the interior of the enclosure. Field effect mobility of hBN-templated devices fabricated from graphene domains grown in this way show room temperature carrier mobilities of $12000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and an absence of weak localization at low temperature. These results indicate a very low concentration of line and point defects in the grown films, which is further supported by Raman and transmission electron microscopic characterization.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Department of Photonics Engineering, Ultrafast Infrared and Terahertz Science, Aarhus University
Number of pages: 10
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: 2D materials
Volume: 4
Issue number: 4
Article number: 045017
ISSN (Print): 2053-1583
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 6.05 SJR 2.813 SNIP 1.072
Web of Science (2017): Impact factor 7.042
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.26 SJR 2.314 SNIP 0.915
Web of Science (2016): Impact factor 6.937
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.89 SJR 4.602 SNIP 1.009
BFI (2014): BFI-level 1
BFI (2013): BFI-level 1
Original language: English
Keywords: Graphene, Chemical vapor deposition, Copper enclosure, Sputter, Single-crystal
Electronic versions:
Suppression of intrinsic roughness in encapsulated graphene

Roughness in graphene is known to contribute to scattering effects which lower carrier mobility. Encapsulating graphene in hexagonal boron nitride (hBN) leads to a significant reduction in roughness and has become the de facto standard method for producing high-quality graphene devices. We have fabricated graphene samples encapsulated by hBN that are suspended over apertures in a substrate and used noncontact electron diffraction measurements in a transmission electron microscope to measure the roughness of encapsulated graphene inside such structures. We furthermore compare the roughness of these samples to suspended bare graphene and suspended graphene on hBN. The suspended heterostructures display a root mean square (rms) roughness down to 12 pm, considerably less than that previously reported for both suspended graphene and graphene on any substrate and identical within experimental error to the rms vibrational amplitudes of carbon atoms in bulk graphite. Our first-principles calculations of the phonon bands in graphene/hBN heterostructures show that the flexural acoustic phonon mode is localized predominantly in the hBN layer. Consequently, the flexural displacement of the atoms in the graphene layer is strongly suppressed when it is supported by hBN, and this effect increases when graphene is fully encapsulated.
Suppression of Intrinsic Roughness in Suspended van der Waals Heterostructures

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Theoretical Nanoelectronics, Theoretical Nanotechnology, National Institute for Materials Science Tsukuba
Contributors: Thomsen, J. D., Gunst, T., Gregersen, S. S., Gammelgaard, L., Jessen, B. S., Mackenzie, D., Bøggild, P., Tanaguchi, T., Booth, T., Watanabe, K.
Publication date: 2017
Peer-reviewed: Yes
Electronic versions:
2017_suppression_of_intrinsic_roughness_in_encapsulated_graphene.pdf
DOIs:
10.1103/PhysRevB.96.014101

Bibliographical note
©2017 American Physical Society
Source: PublicationPreSubmission
Source-ID: 133730441
Research output: Research - peer-review : Journal article – Annual report year: 2017
Working electrode holder and electrochemical cell

The present disclosure relates to a holder for a test object, more specifically to a holder for measuring electrochemical properties of the test object. One embodiment relates to a working electrode holder for measuring electrochemical properties of a front surface of a test object in a liquid, comprising: a housing comprising a bottom surface and a sidewall, the sidewall defining a first opening such that the test object can be placed inside the housing via the first opening and such that the front surface is facing the inner bottom surface; one or more electrically conductive pin(s) fixed to the bottom surface inside the housing such that the front surface of the test object is able to be placed on the pin(s), thereby providing an electrically contacted front surface, such that the electrically contacted front surface is able to operate as the working electrode; a second opening located in the bottom surface and configured for passage of said liquid, such that liquid is able to pass onto the electrically contacted front surface. The holder may be used in an electrochemical cell.

Catalyst Interface Engineering for Improved 2D Film Lift-Off and Transfer

The mechanisms by which chemical vapor deposited (CVD) graphene and hexagonal boron nitride (h-BN) films can be released from a growth catalyst, such as widely used copper (Cu) foil, are systematically explored as a basis for an improved lift-off transfer. We show how intercalation processes allow the local Cu oxidation at the interface followed by selective oxide dissolution, which gently releases the 2D material (2DM) film. Interfacial composition change and selective dissolution can thereby be achieved in a single step or split into two individual process steps. We demonstrate that this method is not only highly versatile but also yields graphene and h-BN films of high quality regarding surface contamination, layer coherence, defects, and electronic properties, without requiring additional post-transfer annealing. We highlight how such transfers rely on targeted corrosion at the catalyst interface and discuss this in context of the wider CVD growth and 2DM transfer literature, thereby fostering an improved general understanding of widely used transfer processes, which is essential to numerous other applications.
Copper Oxidation through Nucleation Sites of Chemical Vapor Deposited Graphene

We investigate the nucleation defect-triggered oxidation of Cu covered by CVD graphene during postannealing in air. The results reveal that different growth conditions may induce imperfect nucleation of graphene, and cause creation of defects near the nucleation point such as pin holes and amorphous carbon. These defects would serve as a pathway for the diffusion of O₂ during thermal annealing, allowing oxidation of Cu to progress gradually from the nucleation center toward the growth edge. The oxidation process follows the graphene morphology closely; the shape of the oxidized area of Cu has a striking resemblance to that of the graphene flakes. Our work demonstrates that inferior graphene nucleation in CVD
processes can compromise the oxidation resistance of a graphene-coated Cu substrate, and indirectly reveal the structure and integrity of graphene, which is of fundamental importance for the quality monitoring and control of graphene growth, for understanding the mechanisms of graphene nucleation and growth, and has implications for graphene's use in electronic and passivation applications.

**General information**

State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene
Contributors: Luo, B., Whelan, P. R., Shivayogimath, A., Mackenzie, D., Bøggild, P., Booth, T.
Number of pages: 7
Pages: 3789-3795
Publication date: 2016
Peer-reviewed: Yes

**Publication information**

Journal: Chemistry of Materials
Volume: 28
Issue number: 11
ISSN (Print): 0897-4756
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 9.74 SJR 4.675 SNIP 1.896
Web of Science (2017): Impact factor 9.89
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 8.89 SJR 4.136 SNIP 1.883
Web of Science (2016): Impact factor 9.466
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 9.38 SJR 3.958 SNIP 2.061
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 8.89 SJR 3.595 SNIP 2.222
Web of Science (2014): Impact factor 8.354
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 8.94 SJR 3.666 SNIP 2.267
Web of Science (2013): Impact factor 8.535
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 8.1 SJR 4.181 SNIP 2.247
Web of Science (2012): Impact factor 8.238
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 7.38 SJR 3.488 SNIP 2.118
Web of Science (2011): Impact factor 7.286
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 3.279 SNIP 1.837
Web of Science (2010): Impact factor 6.4
Intrinsic roughness in suspended van der Waals heterostructures

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon
Contributors: Thomsen, J. D., Bøggild, P., Booth, T.
Publication date: 2016
Peer-reviewed: Yes
Event: Poster session presented at Carbonhagen 2016, Copenhagen, Denmark.
Electronic versions:

Non-destructive integration of graphene for organic light emitting devices

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene, Department of Photonics Engineering, Ultrafast Infrared and Terahertz Science
Contributors: Whelan, P. R., Booth, T., Jepsen, P. U., Bøggild, P.
Number of pages: 1
Publication date: 2016
Peer-reviewed: Yes
URLs:
The hot pick-up technique for batch assembly of van der Waals heterostructures
The assembly of individual two-dimensional materials into van der Waals heterostructures enables the construction of layered three-dimensional materials with desirable electronic and optical properties. A core problem in the fabrication of these structures is the formation of clean interfaces between the individual two-dimensional materials which would affect device performance. We present here a technique for the rapid batch fabrication of van der Waals heterostructures, demonstrated by the controlled production of 22 mono-, bi- and trilayer graphene stacks encapsulated in hexagonal boron nitride with close to 100% yield. For the monolayer devices, we found semiclassical mean-free paths up to 0.9 μm, with the narrowest samples showing clear indications of the transport being affected by boundary scattering. The presented method readily lends itself to fabrication of van der Waals heterostructures in both ambient and controlled atmospheres, while the ability to assemble pre-patterned layers paves the way for complex three-dimensional architectures.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Center for Nanostructured Graphene, Cornell University, Columbia University
Number of pages: 10
Pages: 11894
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Nature Communications
Volume: 7
ISSN (Print): 2041-1723
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 12.41 SJR 6.582 SNIP 2.912
Web of Science (2017): Impact factor 12.353
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 11.8 SJR 6.414 SNIP 2.855
Web of Science (2016): Impact factor 12.124
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 11.23 SJR 6.287 SNIP 2.86
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 10.77 SJR 6.41 SNIP 3.034
Web of Science (2014): Impact factor 11.47
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 9.85 SJR 6.206 SNIP 2.797
Web of Science (2013): Impact factor 10.742
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
Scopus rating (2012): CiteScore 8.32 SJR 5.866 SNIP 2.829
Web of Science (2012): Impact factor 10.015
Characterization of copper oxidation at graphene/copper interfaces by transmission electron microscopy

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Center for Electron Nanoscopy
Contributors: Whelan, P. R., Kostesha, N., Larsen, M. B. B. S., Balogh, Z. I., Bøggild, P., Booth, T.
Number of pages: 1
Publication date: 2015

Host publication information
Title of host publication: Proceedings of AMN-7
Electronic versions: AMN_7_abstract_Patrick_Whelan.pdf
Source: PublicationPreSubmission
Source-ID: 103005608
Research output: Research - peer-review » Conference abstract in proceedings – Annual report year: 2015

Chemical Vapour Deposition of Large Area Graphene
Chemical Vapor Deposition (CVD) is a viable technique for fabrication of large areas of graphene. CVD fabrication is the most prominent and common way of fabricating graphene in industry. In this thesis I have attempted to optimize a growth recipe and catalyst layer for CVD fabrication of uniform, single layer, and high carrier mobility large area graphene. The main goals of this work are; (1) explore the graphene growth mechanics in a low pressure cold-wall CVD system on a copper substrate, and (2) optimize the process of growing high quality graphene in terms of carrier mobility, and crystal structure. Optimization of a process for graphene growth on commercially available copper foil is limited by the number of aluminium oxide particles on the surface of the catalyst. By replacing the copper foil with a thin deposited copper film on a SiO₂/Si or c-plane sapphire wafer the particles can be eliminated. Further opportunities arise when exchanging the copper foil for copper thin film on a wafer e.g. better integration with current cleanroom processing of devices and better control over the copper crystallinity. Typical strategies for controlling the temperature during CVD fabrication of graphene are proportional, integral, and derivative (PID) controllers. The PID controller in a CVD system works off feedback temperatures from a thermocouple. The thermocouples used in this work suffer from degradation at the temperatures and the hydrogen gasses needed for high quality graphene growth. The degradation of thermocouples leads to large variations in the grown graphene. This was solved by controlling the temperature through applying a set power to the heat source, resulting in a more stable temperature from process to process. Micro Raman spectroscopy is used to characterize the structural quality of the grown graphene on the copper surface as well as after a transfer process to a SiO₂ substrate. Raman mapping is especially suited for uniformity characterization on a scale of a few to hundreds of microns. In this work the ratios of the 2D- and G-peak, and the ratio of the D- and the G peak are used as measures of crystalline quality of the CVD grown graphene. I have also used spatially resolved micro Raman spectroscopy to map the full width at half maximum (FWHM) of the graphene G-band and the 2D and G peak positions, for as-grown graphene on copper catalyst layers, for transferred CVD graphene and for micro-mechanically exfoliated graphene. This was done to characterize the effects of a transfer process on the graphene properties. The FWHM(G) to indicate the doping level of graphene, and the ratio of the shifts in the 2D and G bands as an indicator of strain. The transfer process introduces an isotropic, spatially uniform, compressive strain in graphene, and increases the carrier concentration. Copper foil was found to exhibit a polycrystalline surface with a predominantly Cu(001) orientation, through electron backscattering diffraction mapping. Copper thin film deposited on a SiO₂/Si wafer display a polycrystalline nature with the Cu(111) orientation dominating, when the
crystals increase in size. Copper thin film sputtered on a c-plane sapphire wafer shows almost single crystal formation of Cu(111) across a 4 inch wafer. The polycrystalline nature of a thin copper film on a SiO₂/Si wafer was investigated through annealing. A variation in the annealing temperature was found to have a significant effect on the crystal size, while the annealing time was found to have little effect on the crystal sizes. Electronic hall-bar devices were fabricated from CVD graphene grown on copper foil, copper on SiO₂/Si wafers, and copper on sapphire wafers. Preliminary results show the highest carrier mobility was achieved from graphene grown on copper on sapphire, while graphene grown on copper foil showed the lowest carrier mobility.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Center for Nanostructured Graphene, Nanocarbon, DTU Danchip
Contributors: Larsen, M. B. B. S., Bøggild, P., Booth, T., Jørgensen, A. M.
Number of pages: 202
Publication date: 2015

Publication information
Publisher: DTU Nanotech
Original language: English
Electronic versions:
PhD_thesis_Martin_Benjamin_Larsen.pdf
Source: PublicationPreSubmission
Source-ID: 110749612
Research output: Research › Ph.D. thesis – Annual report year: 2015

Defect/oxygen assisted direct write technique for nanopatterning graphene
High resolution nanopatterning of graphene enables manipulation of electronic, optical and sensing properties of graphene. In this work we present a straightforward technique that does not require any lithographic mask to etch nanopatterns into graphene. The technique relies on the damaged graphene to be etched selectively in an oxygen rich environment with respect to non-damaged graphene. Sub-40 nm features were etched into graphene by selectively exposing it to a 100 keV electron beam and then etching the damaged areas away in a conventional oven. Raman spectroscopy was used to evaluate the extent of damage induced by the electron beam as well as the effects of the selective oxidative etching on the remaining graphene.

General information
State: Published
Organisations: Center for Nanostructured Graphene, Department of Micro- and Nanotechnology, Silicon Microtechnology, Nanointegration, Chalmers University of Technology
Number of pages: 7
Pages: 6271-6277
Publication date: 2015
Peer-reviewed: Yes

Publication information
Journal: Nanoscale
Volume: 7
Issue number: 14
ISSN (Print): 2040-3364
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 7.57 SJR 2.934 SNIP 1.442
Web of Science (2017): Impact factor 7.233
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 7.46 SJR 2.789 SNIP 1.441
Web of Science (2016): Impact factor 7.367
Web of Science (2016): Indexed yes
Graphene mobility mapping

Carrier mobility and chemical doping level are essential figures of merit for graphene, and large-scale characterization of these properties and their uniformity is a prerequisite for commercialization of graphene for electronics and electrodes. However, existing mapping techniques cannot directly assess these vital parameters in a non-destructive way. By deconvoluting carrier mobility and density from non-contact terahertz spectroscopic measurements of conductance in graphene samples with terahertz-transparent backgates, we are able to present maps of the spatial variation of both quantities over large areas. The demonstrated non-contact approach provides a drastically more efficient alternative to measurements in contacted devices, with potential for aggressive scaling towards wafers/minute. The observed linear relation between conductance and carrier density in chemical vapour deposition graphene indicates dominance by charged scatterers. Unexpectedly, significant variations in mobility rather than doping are the cause of large conductance inhomogeneities, highlighting the importance of statistical approaches when assessing large-area graphene transport properties.

General information

State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Center for Nanostructured Graphene
Contributors: Buron, J. C. D., Pizzocchero, F., Jepsen, P. U., Petersen, D. H., Caridad, J., Jessen, B. S., Booth, T., Bøggild, P.
In situ TEM electrical characterisation and patterning of graphene

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Technical University of Denmark
Contributors: Thomsen, J. D., Gade, C., Bøggild, P., Booth, T.
In-situ TEM patterning and electrical characterisation of graphene

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanocarbon, Technical University of Denmark
Contributors: Thomsen, J. D., Gade, C., Bøggild, P., Booth, T.
Publication date: 2015
Peer-reviewed: Yes
Event: Poster session presented at Physics Boat Workshop 2015, Helsinki, Finland.
Electronic versions:
Aalto_poster.pdf
Source: PublicationPreSubmission
Source-ID: 127350793
Research output: Research - peer-review › Poster – Annual report year: 2016

Non-destructive electrochemical graphene transfer from reusable thin-film catalysts

We demonstrate an electrochemical method - which we term oxidative decoupling transfer (ODT) - for transferring chemical vapor deposited graphene from physically deposited copper catalyst layers. This copper oxidation-based transfer technique is generally applicable to copper surfaces, and is particularly suitable where the copper is adhered to a substrate such as oxidized silicon. Graphene devices produced via this technique demonstrate 30% higher mobility than similar devices produced by standard catalyst etching techniques. The transferred graphene films cover more than 94% of target substrates - up to 100 mm diameter films are demonstrated here - and exhibit a low Raman D:G peak ratio and a homogenous and continuous distribution of sheet conductance mapped by THz time-domain spectroscopy. By applying a fixed potential of -0.4 V vs. an Ag/AgCl reference electrode - significantly below the threshold for hydrogen production by electrolysis of water - we avoid the formation of hydrogen bubbles at the graphene-copper interface, preventing delamination of thin sputtered catalyst layers from their supporting substrates. We demonstrate the reuse of the same growth substrate for five growth and transfer cycles and prove that this number is limited by the evaporation of Cu during growth of graphene. This technique therefore enables the repeated use of the highest crystallinity and purity substrates without undue increase in cost. (C) 2015 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Center for Nanostructured Graphene, Department of Energy Conversion and Storage, Proton conductors, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Columbia University, AIXTRON
Pages: 397-405
Publication date: 2015
Peer-reviewed: Yes
Unforeseen high temperature and humidity stability of FeCl₃ intercalated few layer graphene

We present the first systematic study of the stability of the structure and electrical properties of FeCl₃ intercalated few-layer graphene to high levels of humidity and high temperature. Complementary experimental techniques such as electrical transport, high resolution transmission electron microscopy and Raman spectroscopy conclusively demonstrate the unforeseen stability of this transparent conductor to a relative humidity up to 100% at room temperature for 25 days, to a temperature up to 150 degrees C in atmosphere and to a temperature as high as 620 degrees C in vacuum, that is more than twice higher than the temperature at which the intercalation is conducted. The stability of FeCl₃ intercalated few-layer graphene together with its unique values of low square resistance and high optical transparency, makes this material an attractive transparent conductor in future flexible electronic applications.

General information

State: Published
Organisations: Center for Nanostructured Graphene, Department of Micro- and Nanotechnology, Nanointegration, University of Exeter
Contributors: Wehenkel, D. J., Bointon, T. H., Booth, T., Bøggild, P., Craciun, M. F., Russo, S.
Publication date: 2015
Peer-reviewed: Yes

Publication information

Journal: Scientific Reports
Volume: 5
Article number: 7609
ISSN (Print): 2045-2322
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.36 SJR 1.533 SNIP 1.245
Web of Science (2017): Impact factor 4.122
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.63 SJR 1.692 SNIP 1.354
Web of Science (2016): Impact factor 4.259
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.3 SJR 2.034 SNIP 1.597
Web of Science (2015): Impact factor 5.228
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.75 SJR 2.163 SNIP 1.554
Web of Science (2014): Impact factor 5.578
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.06 SJR 1.998 SNIP 1.57
Web of Science (2013): Impact factor 5.078
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 2.44 SJR 1.531 SNIP 0.962
Web of Science (2012): Impact factor 2.927
ISI indexed (2012): ISI indexed yes
Automatic identification of single- and/or few-layer thin-film material

One or more digital representations of single- (101) and/or few-layer (102) thin-film material are automatically identified robustly and reliably in a digital image (100), the digital image (100) having a predetermined number of colour components, by - determining (304) a background colour component of the digital image (100) for each colour component, and - determining or estimating (306) a colour component of thin-film material to be identified in the digital image (100) for each colour component by obtaining a pre-determined contrast value (C R; C G; C B) for each colour component and multiplying the respective background colour component with a numerical difference between the pre-determined contrast value (C R; C G; C B) for a given colour component and about 1, - identifying points or parts of the image with all colour components being within a predetermined range of the determined or estimated colour component.

Directed self-assembled crystalline oligomer domains on graphene and graphite: Paper

We observe the formation of thin films of fibre-like aggregates from the prototypical organic semiconductor molecule para-hexaphenylene (p-6P) on graphite thin flakes and on monolayer graphene. Using atomic force microscopy, scanning electron microscopy, x-ray diffraction, polarized fluorescence microscopy, and bireflectance microscopy, the molecular orientations on the surface are deduced and correlated to both the morphology as well as to the high-symmetry directions of the graphitic surface: the molecules align with their long axis at ±11° with respect to a high-symmetry direction. The results show that the graphene surface can be used as a growth substrate to direct the self-assembly of organic molecular thin films and nanofibres, both with and without lithographical processing.
<table>
<thead>
<tr>
<th>Year</th>
<th>BFI Level</th>
<th>Scopus Rating</th>
<th>Web of Science Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>BFI-level 1</td>
<td>CiteScore 3.01 SJR 1.079 SNIP 0.788</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2018</td>
<td>BFI-level 1</td>
<td>CiteScore 2.87 SJR 1.339 SNIP 0.945</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2017</td>
<td>BFI-level 2</td>
<td>CiteScore 3.07 SJR 1.257 SNIP 1.035</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2016</td>
<td>BFI-level 2</td>
<td>CiteScore 3.09 SJR 1.497 SNIP 1.269</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2015</td>
<td>BFI-level 2</td>
<td>CiteScore 2.74 SJR 1.602 SNIP 1.231</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2014</td>
<td>BFI-level 2</td>
<td>CiteScore 3.34 SJR 1.861 SNIP 1.307</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2013</td>
<td>BFI-level 1</td>
<td>CiteScore 3.86 SJR 1.899 SNIP 1.451</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2012</td>
<td>BFI-level 1</td>
<td>CiteScore 1.844 SNIP 1.252</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2011</td>
<td>BFI-level 1</td>
<td>CiteScore 1.809 SNIP 1.27</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2010</td>
<td>BFI-level 1</td>
<td>CiteScore 1.857 SNIP 1.32</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2009</td>
<td>BFI-level 1</td>
<td>CiteScore 1.899 SNIP 1.348</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2008</td>
<td>BFI-level 1</td>
<td>CiteScore 1.938 SNIP 1.364</td>
<td>Indexed yes</td>
</tr>
<tr>
<td>2007</td>
<td>BFI-level 1</td>
<td>CiteScore 1.958 SNIP 1.435</td>
<td>Indexed yes</td>
</tr>
</tbody>
</table>
Electrically continuous graphene from single crystal copper verified by terahertz conductance spectroscopy and micro four-point probe.

The electrical performance of graphene synthesized by chemical vapor deposition and transferred to insulating surfaces may be compromised by extended defects, including for instance grain boundaries, cracks, wrinkles, and tears. In this study, we experimentally investigate and compare the nano- and microscale electrical continuity of single layer graphene grown on centimeter-sized single crystal copper with that of previously studied graphene films, grown on commercially available copper foil, after transfer to SiO2 surfaces. The electrical continuity of the graphene films is analyzed using two noninvasive conductance characterization methods: ultrabroadband terahertz time-domain spectroscopy and micro four-point probe, which probe the electrical properties of the graphene film on different length scales, 100 nm and 10 μm, respectively. Ultrabroadband terahertz time-domain spectroscopy allows for measurement of the complex conductance response in the frequency range 1-15 terahertz, covering the entire intraband conductance spectrum, and reveals that the conductance response for the graphene grown on single crystalline copper intimately follows the Drude model for a barrier-free conductor. In contrast, the graphene grown on commercial copper foil shows a distinctly non-Drude conductance spectrum that is better described by the Drude-Smith model, which incorporates the effect of preferential carrier backscattering associated with extended, electronic barriers with a typical separation on the order of 100 nm. Micro four-point probe resistance values measured on graphene grown on single crystalline copper in two different voltage-current configurations show close agreement with the expected distributions for a continuous 2D conductor, in contrast with previous observations on graphene grown on commercial copper foil. The terahertz and micro four-point probe conductance values of the graphene grown on single crystalline copper shows a close to unity correlation, in contrast with those of the graphene grown on commercial copper foil, which we explain by the absence of extended defects on the microscale in CVD graphene grown on single crystalline copper. The presented results demonstrate that the graphene grown on single crystal copper is electrically continuous on the nanoscopic, microscopic, as well as intermediate length scales.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Experimental Surface and Nanomaterials Physics, Silicon Microtechnology, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Center for Nanostructured Graphene, Capres A/S, McGill University
Number of pages: 8
Pages: 6348-6355
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Nano Letters
Volume: 14
Issue number: 11
ISSN (Print): 1530-6984
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Graphene Edges Dictate the Morphology of Nanoparticles during Catalytic Channeling

We perform in-situ transmission electron microscopy (TEM) experiments of silver nanoparticles channeling on mono-, bi-, and few-layer graphene and discover that the interactions in the one-dimensional particle–graphene contact line are sufficiently strong so as to dictate the three-dimensional shape of the nanoparticles. We find a characteristic faceted shape in particles channeling along graphene 100 directions that is lost during turning and thus represents a dynamic equilibrium state of the graphene–particle system. We propose a model for the mechanism of zigzag edge formation and an explanation of the rate-limiting step for this process, supported by density functional theory (DFT) calculations, and obtain a good agreement between the DFT-predicted and experimentally obtained activation energies of 0.39 and 0.56 eV, respectively. Understanding the origin of the channels’ orientation and the strong influence of the graphene lattice on the dynamic behavior of the particle morphology could be crucial for obtaining deterministic nanopatterning on the atomic scale.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Department of Physics, Theoretical Atomic-scale Physics, Center for Electron Nanoscopy, Center for Atomic-scale Materials Design, Center for Nanostructured Graphene
Pages: 4296–4302
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: The Journal of Physical Chemistry Part C
Volume: 118
Issue number: 8
ISSN (Print): 1932-7447
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.58 SJR 2.135 SNIP 1.147
Web of Science (2017): Impact factor 4.484
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.48 SJR 1.964 SNIP 1.195
Web of Science (2016): Impact factor 4.536
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.68 SJR 1.886 SNIP 1.26
Web of Science (2015): Impact factor 4.509
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 5.08 SJR 2.032 SNIP 1.447
Web of Science (2014): Impact factor 4.772
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 5.14 SJR 2.143 SNIP 1.445
Web of Science (2013): Impact factor 4.835
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 4.98 SJR 2.529 SNIP 1.461
Web of Science (2012): Impact factor 4.814
ISI indexed (2012): ISI indexed yes
Graphene Electrodes: Universal architecture for 2D electronics

The production of graphene and the other 2D materials is presented in the beginning of this thesis. Micromechanical exfoliation is the best method for obtaining relatively small and top quality samples. The invention of Graphene Finder simplifies the procedure of finding the exfoliated flakes. In this work, large area films are exclusively obtained by CVD, mostly on copper films and foils. Several forms of copper are used for CVD growth. A new substrate named ultrafoil is invented to overcome the roughness and contamination of commercially available copper foils. The formation of copper silicide in copper thin films is studied and found to be detrimental for the growth of graphene. The modified synthesis of rGO is introduced, as rGO represents a cheap alternative to CVD for large scale production of graphene.

The transfer of flakes is performed by several methods, such as with PVA/PMMA support, CAB wedging and the pick-up technique with hBN. Several important improvements of the pick-up technique are introduced. These allowed us to transfer any 2D crystals and patterned graphene flakes with PMMA residues. We also developed the drop-down technique, which is used to release any crystal on the surface of the PPC/PDMS. CVD MoS2 and MoSe2 crystals are transferred from oxide with hBN protection by wedging. Ultra clean suspended crystals are obtained by further adaptation of the pick-up technique.

CVD graphene is commonly transferred by etching of the growth substrate or by the bubbling method. Cleaner samples are transferred by combining the drop-down technique and ultrafoil, with hBN flakes protecting the graphene from contacting the polymer support. A new electrochemical transfer method is invented, named ODT. Graphene transferred by ODT shows high coverage compared to other conventional transfer methods. Another important aspect of the ODT is the preservation of the growth catalyst.

THz-TDS is used to generate sheet conductance maps and to characterize the transferred graphene films. Ultrabroad band THz analysis showed a perfect Drude response for graphene grown on copper single crystal and transferred by ODT, while graphene grown on copper foil presented a Drude-Smith response typical of films with extended line defects. M4PP allowed to investigate the continuity of graphene films in the micrometer range. We showed that graphene from Cu single crystal behaved as a perfect 2D conductor, differently from what was previously reported for graphene from Cu foils. An extension of Graphene Finder allowed the generation of high resolution coverage maps that helped characterizing the transferred graphene films.

The pick-up transfer method is used to fabricate structures sandwiched in hBN, in which the electrical connection is obtained by one dimensional edge contact. High quality trilayer encapsulated device is presented, with measured mobility more than 5 times higher than any published result. A new architecture for TMDCs based devices is introduced. The
crystals are encapsulated in hBN and graphene parts intermediate the (edge) contact between gold and the TMDC. In this way, the MoS2 FET with the highest reported mobility to date has been fabricated. The protection by hBN of CVD graphene grown on ultrafoil allowed to fabricate for the first time encapsulated stacks with CVD graphene.

Novel ways of patterning 2D materials are presented. In particular the catalytic etching of graphene by metal nanoparticles is studied. Ag particles in contact with graphene at high temperatures in oxygen are able to form channels aligned along the ZZ direction of graphene. We monitored this phenomenon in-situ with an ETEM. The motion of the particles etching the suspended membrane is discrete, consequence of the interaction with the carbon atoms. DFT calculations supported the hypothesis that it is energetically unfavourable to etch ZZ atoms. The surprisingly strong interaction between the particle and the graphene edge is able to dictate the 3D morphology of the particle. Crystallographic patterning of graphene and hBN is achieved without the catalytic action of metallic particles. Holes are first induced by knock-on damage with high intensity e-beam and enlarged by oxygen at high temperatures.

**General information**
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Molecular Windows
Contributors: Pizzocchero, F., Mølhave, K., Booth, T., Bøggild, P.
Number of pages: 227
Publication date: 2014

**Publication information**
Publisher: Technical University of Denmark (DTU)
Original language: English
Research output: Research › Ph.D. thesis – Annual report year: 2014

**Graphene transport properties upon exposure to PMMA processing and heat treatments**
The evolution of graphene's electrical transport properties due to processing with the polymer polymethyl methacrylate (PMMA) and heat are examined in this study. The use of stencil (shadow mask) lithography enables fabrication of graphene devices without the usage of polymers, chemicals or heat, allowing us to measure the evolution of the electrical transport properties during individual processing steps from the initial as-exfoliated to the PMMA-processed graphene. Heating generally promotes the conformation of graphene to SiO2 and is found to play a major role for the electrical properties of graphene while PMMA residues are found to be surprisingly benign. In accordance with this picture, graphene devices with initially high carrier mobility tend to suffer a decrease in carrier mobility, while in contrast an improvement is observed for low carrier mobility devices. We explain this by noting that flakes conforming poorly to the substrate will have a higher carrier mobility which will however be reduced as heat treatment enhance the conformation. We finally show the electrical properties of graphene to be reversible upon heat treatments in air up to 200°C.

**General information**
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Center for Nanostructured Graphene
Contributors: Gammelgaard, L., Caridad, J., Cagliani, A., Mackenzie, D., Petersen, D. H., Booth, T., Bøggild, P.
Number of pages: 11
Pages: 035005
Publication date: 2014
Peer-reviewed: Yes

**Publication information**
Journal: 2D materials
Volume: 1
Issue number: 3
ISSN (Print): 2053-1583
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 6.05 SJR 2.813 SNIP 1.072
Web of Science (2017): Impact factor 7.042
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.26 SJR 2.314 SNIP 0.915
Web of Science (2016): Impact factor 6.937
Web of Science (2016): Indexed yes
Oxidative Decoupling Transfer: The influence of copper oxidation on CVD graphene transfer

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration
Contributors: Whelan, P. R., Kostesha, N., Pizzocchero, F., Bøggild, P., Booth, T.
Publication date: 2014
Peer-reviewed: Yes

Electronic versions:
Graphene2014_Poster_Patrick_Whelan.pdf
Source: PublicationPreSubmission
Source-ID: 103005588
Research output: Research - peer-review › Poster – Annual report year: 2014

Pattern recognition approach to quantify the atomic structure of graphene

We report a pattern recognition approach to detect the atomic structure in high-resolution transmission electron microscopy images of graphene. The approach provides quantitative information such as carbon-carbon bond lengths and bond length variations on a global and local scale alike. © 2014 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Center for Electron Nanoscopy, Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Photonics Engineering, Structured Electromagnetic Materials, Department of Micro- and Nanotechnology, Nanointegration, Center for Nanostructured Graphene
Transfer induced compressive strain in graphene: Evidence from Raman spectroscopic mapping

We have used spatially resolved micro Raman spectroscopy to map the full width at half maximum (FWHM) of the graphene G-band and the 2D and G peak positions, for as-grown graphene on copper catalyst layers, for transferred CVD graphene and for micromechanically exfoliated graphene, in order to characterize the effects of a transfer process on graphene properties. Here we use the FWHM(G) as an indicator of the doping level of graphene, and the ratio of the shifts in the 2D and G bands as an indicator of strain. We find that the transfer process introduces an isotropic, spatially uniform, compressive strain in graphene, and increases the carrier concentration.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration
Contributors: Larsen, M. B. B. S., Mackenzie, D., Caridad, J., Bøggild, P., Booth, T.
Number of pages: 5
Pages: 113-117
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Microelectronic Engineering
Volume: 121
ISSN (Print): 0167-9317
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 1.87 SJR 0.604 SNIP 0.937
Web of Science (2017): Impact factor 2.02
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.69 SJR 0.589 SNIP 0.949
Web of Science (2016): Impact factor 1.806
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Carbon mediated reduction of silicon dioxide and growth of copper silicide particles in uniform width channels
We show that surface arc-discharge deposited carbon plays a critical intermediary role in the breakdown of thermally grown oxide diffusion barriers of 90 nm on a silicon wafer at 1035°C in an Ar/H2 atmosphere, resulting in the formation of epitaxial copper silicide particles in ≈ 10 μm wide channels, which are aligned with the intersections of the (100) surface of the wafer and the (110) planes on an oxidized silicon wafer, as well as endotaxial copper silicide nanoparticles within the wafer bulk. We apply energy dispersive x-ray spectroscopy, in combination with scanning and transmission electron microscopy of focused ion beam fabricated lammelas and trenches in the structure to elucidate the process of their formation.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration
Contributors: Pizzocchero, F., Bøggild, P., Booth, T.
Pages: 114303
Publication date: 2013
Peer-reviewed: Yes

Publication information
Journal: Journal of Applied Physics
Volume: 114
Issue number: 11
ISSN (Print): 0021-8979
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 2.03 SJR 0.739 SNIP 0.953
Web of Science (2017): Impact factor 2.176
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.72 SJR 0.906 SNIP 0.977
Web of Science (2016): Impact factor 2.068
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.57 SJR 0.821 SNIP 0.996
Web of Science (2015): Impact factor 2.101
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 2.04 SJR 1.039 SNIP 1.197
Web of Science (2014): Impact factor 2.183
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 2.24 SJR 1.155 SNIP 1.286
Web of Science (2013): Impact factor 2.185
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 2.13 SJR 1.312 SNIP 1.291
Web of Science (2012): Impact factor 2.21
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
We propose a description of graphene metamaterial properties through the effective surface conductivity. On the example of tunable absorber we demonstrate that this approach allows for fast and efficient design of functional terahertz devices.
Graphene and Graphene Metamaterials for Terahertz Absorbers

Graphene, due to the possibility to tune its conductivity, is the promising material for a range of the terahertz (THz) applications, such as tunable reflectors, absorbers, modulators, filters and polarization converters. Subwavelength structuring of graphene in order to form metamaterials allows for even more control over the THz waves. In this poster presentation I will show an elegant way to describe the graphene metamaterials and the design of graphene based absorbers. I will also present our recent experimental results on the graphene absorbers characterization.

General information
State: Published
Organisations: Department of Photonics Engineering, Metamaterials, Department of Micro- and Nanotechnology, Nanointegration
Contributors: Andryieuski, A., Pizzocchero, F., Booth, T., Bøggild, P.
Number of pages: 1
Pages: 37
Publication date: 2013

Host publication information
Title of host publication: Carbonhagen 2013 : 4th symposium on carbon nanomaterials
URLs: http://www.dropbox.com/s/gnoudz1fpj0el3l/BOA_CBH2013.pdf

Bibliographical note
Poster presentation.
Source: dtu
Source-ID: u::8534
Research output: Research - peer-review › Conference abstract in proceedings – Annual report year: 2013

Graphene Based Terahertz Absorber Designed With Effective Surface Conductivity Approach

Young field of terahertz (THz) science and technology demands new materials and devices, such as filters, modulators, polarization converters and absorbers. Graphene, a recently discovered single-atom-thick material, provides exciting properties for functional terahertz applications. Graphene is flexible and ultrastrong mechanically, transparent for optical radiation, with high electrical conductivity that can be tuned by electrochemical potential. Structured graphene layers constitute metamaterials that can provide tunable and very unusual electromagnetic properties.

In this contribution we present the description of graphene metamaterial properties through the effective surface conductivity. Such description is very convenient, as it simplifies the design of THz devices, and very natural, since surface conductivity can be measured directly in experiment. We show how to extract the effective conductivity and how to use it in optical design.

We demonstrate a tunable THz perfect absorber, which consists of continuous graphene various structured graphene metamaterials above a metal mirror. Changing the Fermi level from 0 eV to 0.5 eV allows for drastic changes in absorbance from less than 0.1 to 1 in the working range. We demonstrate the possibility of the absorber bandwidth control with the metamaterial’s unit cell geometry.

The results of fabrication and characterization of the THz graphene metamaterials based absorbers will be presented at the conference.

General information
State: Published
Organisations: Department of Photonics Engineering, Metamaterials, Department of Micro- and Nanotechnology, Nanointegration
Contributors: Andryieuski, A., Pizzocchero, F., Booth, T., Bøggild, P., Lavrinenko, A.
Number of pages: 1
Publication date: 2013
Peer-reviewed: Yes
Electronic versions:
Large area THz imaging of electrically controlled graphene conductance

**General information**
State: Published
Organisations: Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Department of Micro- and Nanotechnology, Nanointegration, Technical University of Denmark
Contributors: Møller, M., Buron, J. C. D., Larsen, M. B. B. S., Bøggild, P., Mackenzie, D., Pizzocchero, F., Booth, T., Jepsen, P. U.
Number of pages: 1
Publication date: 2013
Peer-reviewed: Yes
Event: Abstract from International Workshop on Optical Terahertz Science and Technology (OTST 2013), Kyoto Terrsa, Japan.
Electronic versions:
Large_area_THz_mapping.pdf
URLs:
http://www.tanaka.icems.kyoto-u.ac.jp/otst2013/
Source: dtu
Source-ID: u::7944
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2013

Controllable chemical vapor deposition of large area uniform nanocrystalline graphene directly on silicon dioxide

Metal-catalyst-free chemical vapor deposition (CVD) of large area uniform nanocrystalline graphene on oxidized silicon substrates is demonstrated. The material grows slowly, allowing for thickness control down to monolayer graphene. The as-grown thin films are continuous with no observable pinholes, and are smooth and uniform across whole wafers, as inspected by optical-, scanning electron-, and atomic force microscopy. The sp(2) hybridized carbon structure is confirmed by Raman spectroscopy. Room temperature electrical measurements show ohmic behavior (sheet resistance similar to exfoliated graphene) and up to 13% of electric-field effect. The Hall mobility is similar to 40 cm(2)/Vs, which is an order of magnitude higher than previously reported values for nanocrystalline graphene. Transmission electron microscopy, Raman spectroscopy, and transport measurements indicate a graphene crystalline domain size similar to 10 nm. The absence of transfer to another substrate allows avoidance of wrinkles, holes, and etching residues which are usually detrimental to device performance. This work provides a broader perspective of graphene CVD and shows a viable route toward applications involving transparent electrodes. (C) 2012 American Institute of Physics. [doi:10.1063/1.3686135]

**General information**
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Chalmers University of Technology, University of Cambridge, AIXTRON
Contributors: Sun, J., Lindvall, N., Cole, M. T., Wang, T., Booth, T., Bøggild, P., Teo, K. B. K., Liu, J., Yurgens, A.
Number of pages: 6
Publication date: 2012
Peer-reviewed: Yes

**Publication information**
Journal: Journal of Applied Physics
Volume: 111
Issue number: 4
ISSN (Print): 0021-8979
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 2.03 SJR 0.739 SNIP 0.953
Web of Science (2017): Impact factor 2.176
Web of Science (2017): Indexed yes
Micro four-point probe characterization of graphene

General information
State: Published
Organisations: Nanointegration, Department of Micro- and Nanotechnology
Contributors: Klarskov, M. B., Booth, T., Petersen, D. H., Bøggild, P.
Number of pages: 47
Publication date: 2012
Peer-reviewed: Yes
Event: Poster session presented at 3rd Symposium on Graphene and Carbon Nanotubes, Copenhagen, Denmark.
Research output: Research - peer-review » Poster – Annual report year: 2012

Discrete Dynamics of Nanoparticle Channelling in Suspended Graphene
We have observed a previously undescribed stepwise oxidation of mono- and few layer suspended graphene by silver nanoparticles in situ at subnanometer scale in an environmental transmission electron microscope. Over the range of 600–850 K, we observe crystallographically oriented channelling with rates in the range 0.01–1 nm/s and calculate an activation energy of 0.557 ± 0.016 eV. We present a discrete statistical model for this process and discuss the implications for accurate nanoscale patterning of nanoscale systems.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Center for Electron Nanoscopy, Nanointegration Group, NanoSystemsEngineering Section, FEI Company bb.
Contributors: Booth, T., Pizzocchero, F., Andersen, H., Hansen, T. W., Wagner, J. B., Jinschek, J. R., Dunin-Borkowski, R. E., Hansen, O., Bøggild, P.
Pages: 2689-2692
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Nano Letters
Volume: 11
Issue number: 7
ISSN (Print): 1530-6984
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 13.07
Web of Science (2017): Impact factor 12.08
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 13.4
Web of Science (2016): Impact factor 12.712
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 14.76
Fast and direct measurements of the electrical properties of graphene using micro four-point probes

We present measurements of the electronic properties of graphene using a repositionable micro four-point probe system, which we show here to have unique advantages over measurements made on lithographically defined devices; namely speed, simplicity and lack of a need to pattern graphene. Measurements are performed in ambient, vacuum and controlled environmental conditions using an environmental scanning electron microscope (SEM). The results are comparable to previous results for microcleaved graphene on silicon dioxide (SiO2). We observe a pronounced hysteresis of the charge neutrality point, dependent on the sweep rate of the gate voltage; and environmental measurements provide insight into the sensor application prospects of graphene. The method offers a fast, local and non-destructive technique for electronic measurements on graphene, which can be positioned freely on a graphene flake.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Solar Energy Programme, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Capres A/S
Self catalyzed GaAs nanowires grown on Si-treated GaAs substrates were studied with a transmission electron microscope before and after annealing at 600 °C. At room temperature the nanowires have a zincblende structure and are locally characterized by a high density of rotational twins and stacking faults. Selected area diffraction patterns and high-resolution transmission electron microscopy images show that nanowires undergo structural modifications upon annealing, suggesting a decrease of defect density following the thermal treatment.

In situ transmission electron microscopy analyses of thermally annealed self catalyzed GaAs nanowires grown by molecular beam epitaxy

Self catalyzed GaAs nanowires grown on Si-treated GaAs substrates were studied with a transmission electron microscope before and after annealing at 600 °C. At room temperature the nanowires have a zincblende structure and are locally characterized by a high density of rotational twins and stacking faults. Selected area diffraction patterns and high-resolution transmission electron microscopy images show that nanowires undergo structural modifications upon annealing, suggesting a decrease of defect density following the thermal treatment.

Nanomechanical resonators were cut out of thin membrane chips, which have been prefabricated using standard cleanroom processing. We have demonstrated the fabrication of double-clamped beams with feature sizes down to 200 nm using a fabrication time of 30 min per device. Afterwards, the dynamic and structural properties of a double-clamped beam were measured after subsequent Joule heating events in order to ascertain the dependence of the internal structure on the Q-factor and resonant frequency of the device. It was observed that a change from amorphous to polycrystalline silicon structure significantly increased the resonant frequency as well as the Q-factor of the nanomechanical resonator.

In Situ Tuning of Focused-Ion-Beam Defined Nanomechanical Resonators Using Joule Heating

Nanomechanical resonators have a huge potential for a variety of applications, including high-resolution mass sensing. In this paper, we demonstrate a novel rapid prototyping method for fabricating nanoelectromechanical systems using focused-ion-beam milling as well as in situ electromechanical characterization using a transmission electron microscope. Nanomechanical resonators were cut out of thin membrane chips, which have been prefabricated using standard cleanroom processing. We have demonstrated the fabrication of double-clamped beams with feature sizes down to 200 nm using a fabrication time of 30 min per device. Afterwards, the dynamic and structural properties of a double-clamped beam were measured after subsequent Joule heating events in order to ascertain the dependence of the internal structure on the Q-factor and resonant frequency of the device. It was observed that a change from amorphous to polycrystalline silicon structure significantly increased the resonant frequency as well as the Q-factor of the nanomechanical resonator.
Aside from allowing detailed studies of the correlation between internal structure and nanomechanical behavior on an individual rather than a statistical basis, the combination of a short turnaround time and in situ nonlithographic tuning of the properties provide a flexible approach to the development and prototyping of nanomechanical devices.

**General information**

**State:** Published

**Organisations:** Department of Micro- and Nanotechnology, MEMS-AppliedSensors Group, MicroElectroMechanical Systems Section

**Contributors:** Homann, L. V., Booth, T., Lei, A., Petersen, D. H., Davis, Z. J., Bøggild, P.

**Pages:** 1074-1080

**Publication date:** 2011

**Peer-reviewed:** Yes

**Publication information**

**Journal:** IEEE Journal of Microelectromechanical Systems

**Volume:** 20

**Issue number:** 5

**ISSN (Print):** 1057-7157

**Ratings:**

- BFI (2019): BFI-level 2
- Web of Science (2019): Indexed yes
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 2
- Scopus rating (2017): CiteScore 2.76 SJR 0.734 SNIP 1.376
- Web of Science (2017): Impact factor 2.475
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): CiteScore 2.09 SJR 0.667 SNIP 1.209
- Web of Science (2016): Impact factor 2.124
- BFI (2015): BFI-level 2
- Scopus rating (2015): CiteScore 2.47 SJR 0.764 SNIP 1.527
- Web of Science (2015): Impact factor 1.939
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Scopus rating (2014): CiteScore 2.22 SJR 0.836 SNIP 1.539
- Web of Science (2014): Impact factor 1.754
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Scopus rating (2013): CiteScore 2.81 SJR 0.929 SNIP 1.786
- Web of Science (2013): Impact factor 1.915
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Scopus rating (2012): CiteScore 2.7 SJR 1.143 SNIP 1.928
- Web of Science (2012): Impact factor 2.129
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 1
- Scopus rating (2011): CiteScore 2.83 SJR 1.19 SNIP 1.784
- Web of Science (2011): Impact factor 2.098
- ISI indexed (2011): ISI indexed yes
- Web of Science (2011): Indexed yes
- BFI (2010): BFI-level 1
- Scopus rating (2010): SJR 1.226 SNIP 1.881
- Web of Science (2010): Impact factor 2.157
- BFI (2009): BFI-level 1
- Scopus rating (2009): SJR 1.451 SNIP 1.821

**Abstract**

Aside from allowing detailed studies of the correlation between internal structure and nanomechanical behavior on an individual rather than a statistical basis, the combination of a short turnaround time and in situ nonlithographic tuning of the properties provide a flexible approach to the development and prototyping of nanomechanical devices.

**Keywords**

- Nanomechanical devices
- Correlation
- Internal structure
- Turnaround time
- Tuning
- Flexible approach

**References**

Optimization of FIB milling for rapid NEMS prototyping

We demonstrate an optimized milling technique to focused ion beam (FIB) milling in template silicon membranes for fast prototyping of nanoelectromechanical systems (NEMS). Using a single-pass milling strategy the highly topology dependent sputtering rate is boosted and shorter milling time is achieved. Drift independence is obtained for small critical features using a radial scan strategy, and a back scan routine ensures minimal line width deviation removing redeposited material. Milling a design similar to a nano four-point probe with a pitch down to 400nm we display what optimized FIB milling in NEMS development can accomplish.

General information

State: Published
Organisations: Nanointegration Group, NanoSystemsEngineering Section, Department of Micro- and Nanotechnology
Contributors: Malm, B., Petersen, D. H., Lei, A., Booth, T., Homann, L. V., Bøggild, P.
Pages: 2671-2674
Publication date: 2011
Peer-reviewed: Yes

Publication information

Journal: Microelectronic Engineering
Volume: 88
Issue number: 8
ISSN (Print): 0167-9317
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 1.87 SJR 0.604 SNIP 0.937
Web of Science (2017): Impact factor 2.02
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.69 SJR 0.589 SNIP 0.949
Web of Science (2016): Impact factor 1.806
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Customizable in situ TEM devices fabricated in freestanding membranes by focused ion beam milling

Nano- and microelectromechanical structures for in situ operation in a transmission electron microscope (TEM) were fabricated with a turnaround time of 20 min and a resolution better than 100 nm. The structures are defined by focused ion beam (FIB) milling in 135 nm thin membranes of single crystalline silicon extending over the edge of a pre-fabricated silicon microchip. Four-terminal resistance measurements of FIB-defined nanowires showed at least two orders of magnitude increase in resistivity compared to bulk. We show that the initial high resistance is due to amorphization of silicon, and that current annealing recrystallizes the structure, causing the electrical properties to partly recover to the pristine bulk resistivity. In situ imaging of the annealing process revealed both continuous and abrupt changes in the crystal structure, accompanied by instant changes of the electrical conductivity. The membrane structures provide a simple way to design electron-transparent nanodevices with high local temperature gradients within the field of view of the TEM, allowing detailed studies of surface diffusion processes. We show two examples of heat-induced coarsening of gold on a narrow freestanding bridge, where local temperature gradients are controlled via the electrical current paths. The separation of device processing into a one-time batch-level fabrication of identical, generic membrane templates, and subsequent device-specific customization by FIB milling, provides unparalleled freedom in device layout combined with very short effective fabrication time. This approach significantly speeds up prototyping of nanodevices such as resonators, actuators, sensors and scanning probes with state-of-art resolution.

General information
State: Published
Organisations: Department of Micro- and Nanotechnology, Nanointegration, Nanointegration Group, NanoSystems Engineering Section, DTU Danchip
Contributors: Lei, A., Petersen, D. H., Booth, T., Homann, L. V., Kallesøe, C., Sardan Sukas, Ö., Gyristing, Y., Mølhave, K., Bøggild, P.
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Nanotechnology
Volume: 21
Issue number: 40
ISSN (Print): 0957-4484
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.01 SJR 1.079 SNIP 0.788
Web of Science (2017): Impact factor 3.404
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.87 SJR 1.339 SNIP 0.945
Web of Science (2016): Impact factor 3.44
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.07 SJR 1.257 SNIP 1.035
Web of Science (2015): Impact factor 3.573
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.09 SJR 1.497 SNIP 1.269
Web of Science (2014): Impact factor 3.821
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.74 SJR 1.602 SNIP 1.231
Web of Science (2013): Impact factor 3.672
ISI indexed (2013): ISI indexed yes
Fast FIB-milled Electron-transparent Microchips for in situ TEM Investigations

In this work we present a fast approach to 50 nm resolution structures defined in a generic TEM-chip template in few minutes. While creating complex electrical and NEMS circuits for a specific in situ TEM experiment can be a cumbersome process, microchips with 100 nm thin flakes of single crystalline silicon and silicon nitride membrane templates suspended from the edge, can be patterned in less than 15 minutes using focused ion beam milling. This approach allows a FIB-SEM user to create free-form NEMS structures for nano resonators, actuators, heaters, resistors or other structures for insitu TEM devices or materials research using the same template. We demonstrate insitu environmental TEM analysis of Au film migration on silicon during resistive heating of a microbridge, and show how the conductance of focused ion beam milled single crystalline silicon nanowires can be adjusted insitu over two decades using a high current to recrystallise the structure.

General information
Manipulation and in situ transmission electron microscope characterization of sub-100 nm nanostructures using a microfabricated nanogripper

We present here a polysilicon electrothermal microfabricated nanogripper capable of manipulating nanowires and nanotubes in the sub-100 nm range. The nanogripper was fabricated with a mix and match microfabrication process, combining high throughput of photolithography with 10 nm resolution of electron beam lithography. Vertically grown III–V nanowires with a diameter of 70 nm were picked up using the nanogripper, allowing direct transfer of the nanogripper-nanowire ensemble into a transmission electron microscope (TEM) for structural characterization. By refining the end-effectors with focused ion beam milling and subsequently coating these with Au, the nanogripper could lift up laterally aligned single-walled carbon nanotubes from a 1 µm wide trench, while immediately making good electrical contact. One such carbon nanotube was structurally and electrically characterized real-time in TEM, showing a breakdown current density of approximately 0.5 × 1012Am−2. The nanogripper is the smallest microfabricated gripper to date and is the first tool showing repeatable, 3D nanomanipulation of sub-100 nm structures.
Nanobits, Membranes and Micro Four-Point Probes: Customizable Tools for insitu Manipulation and Characterisation of Nanostructures

We present a range of highly adaptable microtools for direct interaction with nanoscale structures; (i) semi automatic pick-and-place assembly of multiwalled carbon nanotubes onto cantilevers for high-aspect ratio scanning probe microscopy, using electrothermal microgrippers inside a SEM. Topology optimisation was used to calculate the optimal gripper shape defined by the boundary conditions, resulting in 10-100 times better performance. By instead pre-defining detachable tips using electron beam lithography, free-form scanning probe tips (Nanobits) can be mounted in virtually any position on a cantilever; (ii) scanning micro four point probes allow fast, non-destructive mapping of local electrical properties (sheet resistance and Hall mobility) and hysteresis effects of graphene sheets; (iii) sub 100 nm freestanding devices with wires, heaters, actuators, sensors, resonators and probes were defined in a 100 nm thin membrane with focused ion beam milling. By patterning generic membrane templates (Membranes) the fabrication time of a TEM compatible NEMS device is effectively reduced to less around 20 minutes.

Real-time Observations of Metal Nanoparticle Etching in Ultraclean Suspended Graphene

We describe a range of experimental conditions under which we observe unprecedented long-term stability in suspended graphene membranes under intense electron beam irradiation in environmental TEM. The stability and lack of beam-induced contamination permits us to study in real-time the dynamics of high-temperature catalytic etching of graphene sheets by metal nanoparticles. We observe rich particle dynamics with several distinct modes of graphene etching, and consider in which way this may lead to crystallographic nanolithography on a large scale.

Conducting FIB milled nanowires, MNE 2009

We present a range of highly adaptable microtools for direct interaction with nanoscale structures; (i) semi automatic pick-and-place assembly of multiwalled carbon nanotubes onto cantilevers for high-aspect ratio scanning probe microscopy, using electrothermal microgrippers inside a SEM. Topology optimisation was used to calculate the optimal gripper shape defined by the boundary conditions, resulting in 10-100 times better performance. By instead pre-defining detachable tips using electron beam lithography, free-form scanning probe tips (Nanobits) can be mounted in virtually any position on a cantilever; (ii) scanning micro four point probes allow fast, non-destructive mapping of local electrical properties (sheet resistance and Hall mobility) and hysteresis effects of graphene sheets; (iii) sub 100 nm freestanding devices with wires, heaters, actuators, sensors, resonators and probes were defined in a 100 nm thin membrane with focused ion beam milling. By patterning generic membrane templates (Membranes) the fabrication time of a TEM compatible NEMS device is effectively reduced to less around 20 minutes.
Fine structure constant defines visual transparency of graphene

There are few phenomena in condensed matter physics that are defined only by the fundamental constants and do not depend on material parameters. Examples are the resistivity quantum, h/e2 (h is Planck's constant and e the electron charge), that appears in a variety of transport experiments and the magnetic flux quantum, h/e, playing an important role in the physics of superconductivity. By and large, sophisticated facilities and special measurement conditions are required to observe any of these phenomena. We show that the opacity of suspended graphene is defined solely by the fine structure constant, \( a = \frac{e^2}{hc} = \frac{1}{137} \) (where c is the speed of light), the parameter that describes coupling between light and relativistic electrons and that is traditionally associated with quantum electrodynamics rather than materials science.

Despite being only one atom thick, graphene is found to absorb a significant (\( \rho_a = 2.3\% \)) fraction of incident white light, a consequence of graphene's unique electronic structure.
Graphene-Based Liquid Crystal Device

Graphene is only one atom thick, optically transparent, chemically inert and an excellent conductor. These properties seem to make this material an excellent candidate for applications in various photonic devices that require conducting but transparent thin films. In this letter we demonstrate liquid crystal devices with electrodes made of graphene which show excellent performance with a high contrast ratio. We also discuss the advantages of graphene compared to conventionally-used metal oxides in terms of low resistivity, high transparency and chemical stability.
Macroscopic graphene membranes and their extraordinary stiffness

The properties of suspended graphene are currently attracting enormous interest, but the small size of available samples and the difficulties in making them severely restrict the number of experimental techniques that can be used to study the
optical, mechanical, electronic, thermal, and other characteristics of this one-atom-thick material. Here, we describe a new and highly reliable approach for making graphene membranes of a macroscopic size (currently up to 100 µm in diameter) and their characterization by transmission electron microscopy. In particular, we have found that long graphene beams supported by only one side do not scroll or fold, in striking contrast to the current perception of graphene as a supple thin fabric, but demonstrate sufficient stiffness to support extremely large loads, millions of times exceeding their own weight, in agreement with the presented theory. Our work opens many avenues for studying suspended graphene and using it in various micromechanical systems and electron microscopy.

General information
State: Published
Organisations: University of Manchester, Graphene Industries Limited, Daresbury Laboratory, Radboud University Nijmegen
Number of pages: 5
Pages: 2442-2446
Publication date: 2008
Peer-reviewed: Yes

Publication information
Journal: NANO LETTERS
Volume: 8
Issue number: 8
ISSN (Print): 1530-6984
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 13.07
Web of Science (2017): Impact factor 12.08
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 13.4
Web of Science (2016): Impact factor 12.712
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 14.76
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 14.04
Web of Science (2014): Impact factor 13.592
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 14.23
Web of Science (2013): Impact factor 12.94
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 13.78
Web of Science (2012): Impact factor 13.025
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 13.83
Web of Science (2011): Impact factor 13.198
One of the most severe challenges man is facing today is to fulfill the need for energy without harmful environmental consequences. This complicated, grand challenge must be met by a wide range of solutions; among these are more efficient use of resources and replacement of fossil fuels by renewable energy sources. Any sustainable, renewable...
energy system must directly or indirectly rely on solar energy. Photovoltaic or solar cells are already efficient and reliable sources of electricity from solar light, but even though the cost has decreased significantly in recent years, solar cells are still far too costly for a competitive production of bulk grid power. The challenge within the solar cell field is thus to reduce the costs involved in solar cell production without sacrificing efficiency and reliability; actually, the efficiency should better improve towards 25% or more, since the cell efficiency strongly affects the overall economy of a solar cell power plant. Currently, most of the solar cell market is based on 180-300 micrometer thick crystalline silicon wafers, and approximately 50% of the cost is due to the cost of the material. To reduce material costs thin film cells are promising alternatives, but a limitation in thin film solar cell technologies is that the absorbance of light is quite weak in particular for indirect band gap materials like silicon. This limitation may be lifted by application of photon trapping strategies that can increase the absorptivity of thin photo-absorbers by orders of magnitude at longer wavelengths. Another proved approach in solar cell optimization is carrier selective contacts, such as conventional amorphous silicon, or wide bandgap metal oxide semiconductors. In this project, we will explore several new ideas for novel silicon-based solar cells to develop efficient solar cells that can be fabricated in a low thermal budget, low-cost fabrication procedure using only abundant elements. The main photo-absorber will be lightly doped p-type silicon (1.12 eV band gap) with a thin n-type TiO2 (3.2 eV band gap) film on top. This structure forms a p-n heterojunction that effectively separates the photo-generated electron hole-pairs, since the titanium and silicon conduction bands are aligned facilitating electron transport, while a ~2 eV energy barrier will prevent hole transport. The electrons transported through the titanium to the surface will be conducted laterally by a metal grid or continuous transparent conductive oxides such as Aluminum Zinc Oxide (AZO) with high conductivity, highly transparent (loss 10 %) electrode layer. On the backside, silicon will be coated with complementary to TiO2 thin film of NiO. NiO is p-type wide bandgap (3.6 eV) semiconductor. In connection to Si it will form p-p type heterojunction with excellent valence band matching, and creating hole conducting and electron blocking layer. A back contact will be formed using a high work-function metal to form additional a potential barrier against electron transport, while the holes are easily conducted to the metal. This basic structure will be combined with micro and nanostructuring of the silicon surface prior to fabrication to form a light trapping structure. All fabrication procedures may be done at temperatures close to room temperature with a maximum of ~200oC necessary in a single step, and thus the thermal budget becomes unusually low. At the same time, a high open circuit voltage for the structure is expected due to the efficient carrier separation in the structure. The overall project will have four main research phases. In the first phase of the project, the basic TiO2-Si heterostructure will be optimized on planar silicon wafers. Here the focus will be on the development of optimized fabrication procedures that results in high-performance junctions and efficient lateral transport. In this phase of the project, we also want to fabricate silicon alumina-titania heterostructures. Alumina has properties similar to titania: a wide bandgap and transparency to visible wavelengths, hole transport blocking and passivation of a silicon surface. In the process, alumina will be deposited on top of silicon and then the lithographic windows will be opened for titania deposition and formation of localized titania-silicon heterojunctions. On top of titania areas aluminum contacts will be introduced. It is planned to fabricate and test such structures since they have a potential to show both high open circuit voltage and short circuit current. Other metal with close by work function will be tested to minimize current blocking effects in diode structure. In the second stage, NiO-Si isotype heterostructure will be tested and optimized to meet the best ohmic (hole conductive) properties. We will fabricate and characterize NiO-Si structure similar to TiO2-Si structure. Next micro- and nanostructured silicon surfaces, including “Black silicon”, for light trapping will be developed and characterized. In this stage, nanostructured surfaces should be optimized to obtain the lowest surface recombination velocity in comparison to plain silicon. Then the optimized heterostructure cell fabrication procedure will be ported to these structures. Finally, after the previous three stages will be developed, different solar cell architectures will be tested for solar cell fabrication and characterization. We consider Pasha, HIT and IBC architecture as the most promising for solar cell test since they showed the world records of efficiencies for conventional silicon solar cells. Plakhotnyuk, M., PhD Student, Department of Micro- and Nanotechnology Hansen, O., Main Supervisor, Experimental Surface and Nanomaterials Physics Booth, T., Supervisor, Department of Micro- and Nanotechnology Schmidt, M. S., Supervisor, Department of Micro- and Nanotechnology Jørgensen, A. M., Examiner, DTU Danchip Isabella, O., Examiner Madsen, M., Examiner Madsen, M., Examiner Project ID: 3315 Institut stipendie (DTU) 15/02/2014 → 06/06/2018 Keywords: Silicon Solar Cell, ALD, Carrier Selective Contacts, Transition Metal Oxides Award relations: Silicon heterostructure solar cells Project: PhD

Ballistic Transport in van der Waals Heterostructure Devices Zultak, J., PhD Student, Department of Micro- and Nanotechnology Bøggild, P., Main Supervisor, Center for Nanostructured Graphene Booth, T., Supervisor, Center for Nanostructured Graphene Thygesen, K. S., Examiner, Department of Physics Chernikov, A., Examiner Withers, F., Examiner
Fabrication of Van-der-Waals Heterostructures by Chemical Vapour Deposition
Shivayogimath, A., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Mølhave, K., Examiner, Molecular Windows
Lemme, M. C., Examiner
Sun, J., Examiner, Department of Mechanical Engineering
Lemme, M. C., Examiner
Anden EU-finansiering
01/10/2014 → 07/02/2018
Award relations: Fabrication of Van-der-Waals Heterostructures by Chemical Vapour Deposition
Project: PhD

PhD Scholarship in Nanoscale Imaging of the Aqueous Processes of Precipitation, Dispersion and Imbition
Lagana, S., PhD Student, Department of Micro- and Nanotechnology
Mølhave, K., Main Supervisor, Molecular Windows
Burrows, A., Supervisor, DTU Danchip
Stenby, E. H., Supervisor, Department of Chemistry
Booth, T., Examiner, Department of Micro- and Nanotechnology
Davis, Z. J., Examiner, DTU Danchip
Xu, Q., Examiner
Xu, Q., Examiner
Samfinansieret - Andet
15/05/2014 → 13/09/2017
Award relations: PhD Scholarship in Nanoscale Imaging of the Aqueous Processes of Precipitation, Dispersion and Imbition
Project: PhD

Nanoengineered Graphene Devices
Klarskov, M. B., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Craciun, M. F., Examiner
Kjelstrup-Hansen, J., Examiner, Department of Micro- and Nanotechnology
Forskningsrådsfinansiering
01/02/2009 → 27/05/2013
Award relations: Nanoengineered Graphene Devices
Project: PhD
**Suspended Nanopatterned Graphene Devices**
Gammelgaard, L., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Jauho, A., Supervisor, Theoretical Nanotechnology
Brandbyge, M., Examiner, Department of Physics
Hill, E. W., Examiner
Lemme, M. C., Examiner
Hill, E. W., Examiner
Lemme, M. C., Examiner
Anden EU-finansiering
15/08/2013 → 07/12/2016
Award relations: Suspended Nanopatterned Graphene Devices
Project: PhD

**Graphene Growth and Transfer - DAGATE**
Whelan, P. R., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Hübner, J., Examiner, DTU Danchip
Hübner, J., Examiner, DTU Danchip
Sun, J., Examiner
Sun, J., Examiner
Düsberg, G. S., Examiner
Sun, J., Examiner
Institut, samfinansiering
15/08/2013 → 08/03/2017
Award relations: Graphene Growth and Transfer - DAGATE
Project: PhD

**In-situ TEM Studies of Nanowire-based Batteries**
Møller-Nilsen, R. E. R., PhD Student, Department of Micro- and Nanotechnology
Mølhave, K., Main Supervisor, Molecular Windows
Norby, P., Supervisor, Department of Energy Conversion and Storage
Wagner, J. B., Supervisor, Center for Electron Nanoscopy
Booth, T., Examiner, Department of Micro- and Nanotechnology
Alloyeau, D., Examiner
Tang, P. T., Examiner, Institute for Product Development
Alloyeau, D., Examiner
Institut, samfinansiering
15/12/2012 → 15/06/2016
Award relations: In-situ TEM Studies of Nanowire-based Batteries
Project: PhD

**Graphene Electrodes for Molecular Electronics**
Pizzocchero, F., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Mølhave, K., Supervisor, Department of Micro- and Nanotechnology
Brandbyge, M., Examiner, Department of Physics
Hornekær, L., Examiner
Yurgens, A., Examiner
1/3 FUU, 1/3 inst 1/3 Andet
15/01/2011 → 26/09/2014
Award relations: Graphene Electrodes for Molecular Electronics
Project: PhD

**Large Area growth of graphene for transparent electrodes**
Larsen, M. B. B. S., PhD Student, Department of Micro- and Nanotechnology
Bøggild, P., Main Supervisor, Department of Micro- and Nanotechnology
Booth, T., Supervisor, Department of Micro- and Nanotechnology
Hübner, J., Supervisor, DTU Danchip
Jørgensen, A. M., Supervisor, DTU Danchip
Mogensen, K. B., Examiner, Department of Micro- and Nanotechnology
Dijon, J., Examiner
Pedersen, S. U., Examiner
Institut stipendie (DTU)
01/06/2011 → 18/06/2015
Award relations: Large Area growth of graphene for transparent electrodes
Project: PhD