Nanoscale characterization of single layer graphene on α-Al_2O_3 (0001)

Henrik Wördenweber[1], Silvia Karthäuser[1], Annika Grundmann[2], Zhaodong Wang[1], Stephan Aussen[1], Holger Kalisch[2], Andrei Vescan[2], Michael Heuken[2,3], Rainer Waser[1,4], and Susanne Hoffmann-Eifert[1]

[1] Peter Grünberg Institute 7&10, Forschungszentrum Jülich GmbH and JARA-FIT, 52425 Jülich, Germany; [2] Compound Semiconductor Technology, RWTH Aachen University, 52074 Aachen, Germany; [3] AIXTRON SE, 52134 Herzogenrath, Germany; [4] Institute of Materials in Electrical Engineering and Information Technology II and JARA-FIT, RWTH Aachen University, 52074 Aachen, Germany

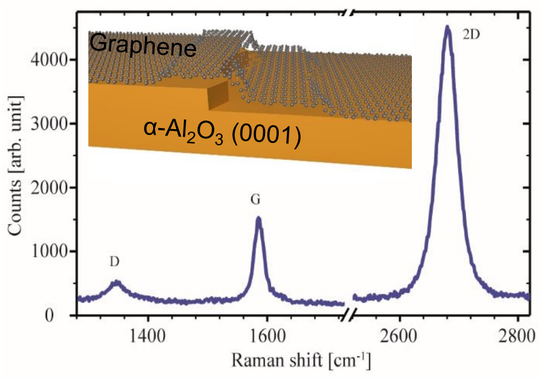
Motivation and methods

Direct growth of two-dimensional (2D) materials on semiconductor technology compatible substrates is identified as a key factor for future electronic applications.[1] Recently, metal-free chemical vapor deposition (CVD) of high-quality single-layer graphene (SLG) on c-plane sapphire has been demonstrated. This could lead towards graphene as technologically viable bottom electrode without preceding transfer.[2] Utilizing this material for the design of nanoscale devices requires comprehensive knowledge of the local electronic properties of the SLG/sapphire system. This was approached with a multi-scale analysis of industrial quality [3] SLG grown on H_2-treated α-Al_2O_3 (0001) utilizing various analytical techniques:

- Raman spectroscopy
- Scanning electron microscopy (SEM)
- X-ray photoelectron spectroscopy (XPS)
- Atomic force microscopy (AFM)
- Conductive Atomic force microscopy (C-AFM)
- Scanning tunneling microscopy (STM)
- Scanning tunneling spectroscopy (STS)

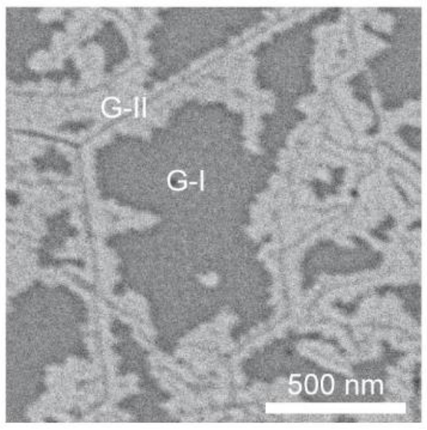
Wafer-scale analysis

Raman Spectroscopy



Distinct graphene peaks with intensity ratios of 2D/G = 3.3 and D/G = 0.2 accounting for SLG with low defect density.

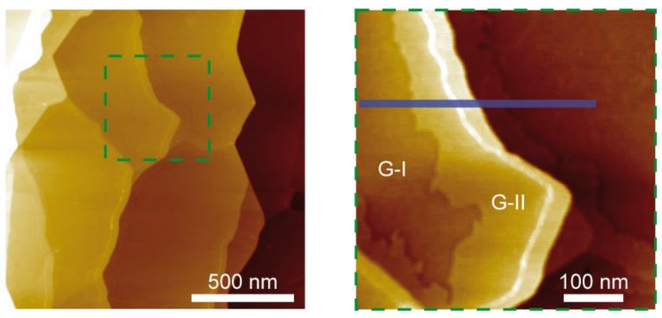
SEM Image



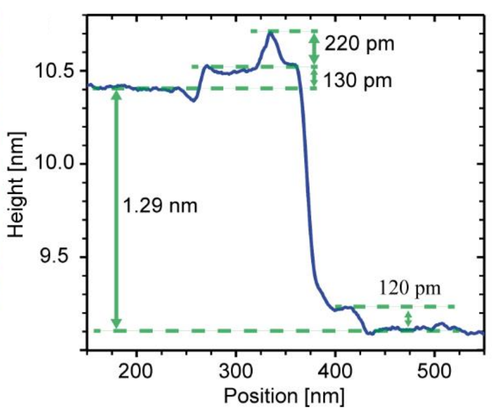
Two distinct graphene regions:
G-I on the sapphire terraces
G-II close to the sapphire step edges

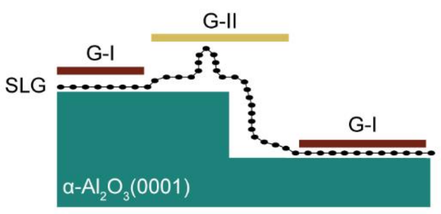
Sub-micrometer analysis

AFM topography (tapping mode)



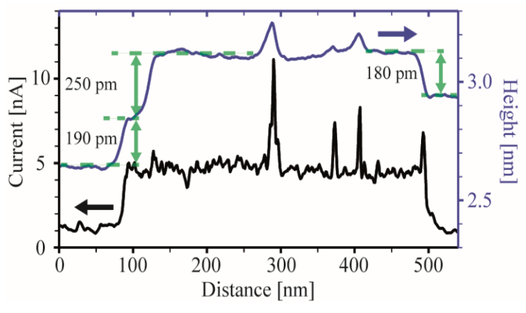
Large-area AFM images (left) show homogeneous SLG without signs of cracks or defects confirming the Raman results. Sapphire step edges and capillary wrinkles can be observed. In the higher resolution AFM image (middle) a vertical height variation between two graphene regions is visible.



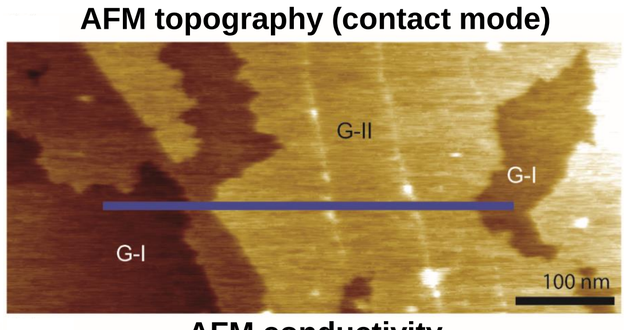


Combined AFM topography (contact mode) & C-AFM analysis

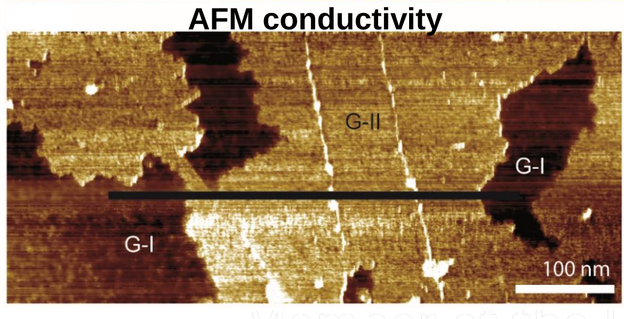
- No change of conductivity at a sapphire step edge (250 pm).
- The conductivity on the detached graphene (G-II) is nearly four times as high as that on the weakly bonded graphene (G-I).



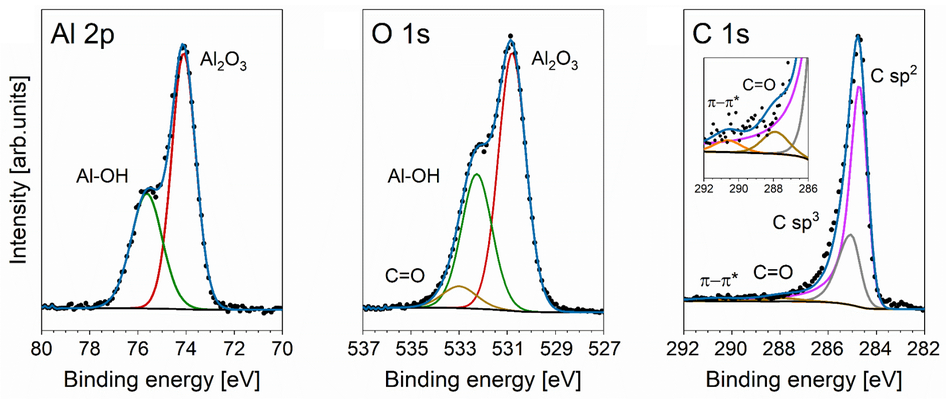
AFM topography (contact mode)



AFM conductivity



Surface chemical analysis



XPS study

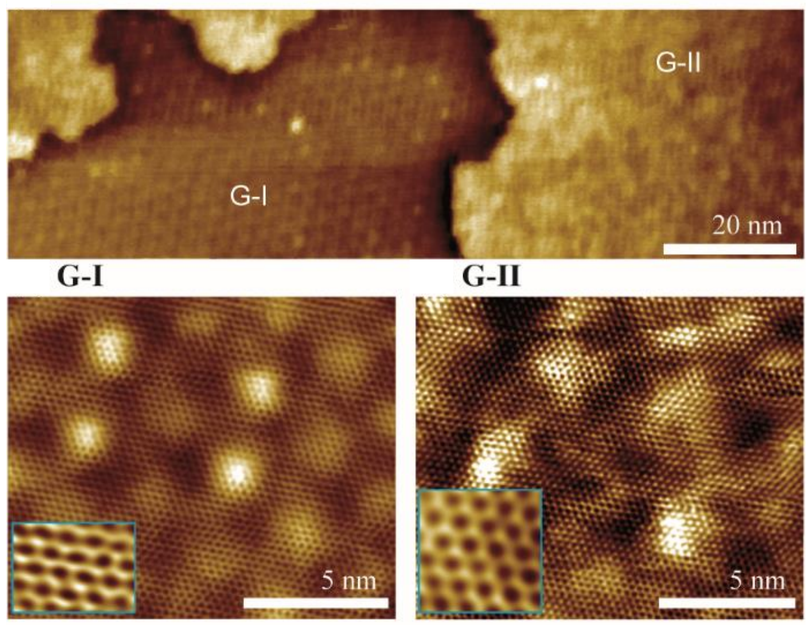
- OH-terminated sapphire surface
- sp^2-hybridized carbon
  ⇨ graphene

Atomic-scale analysis

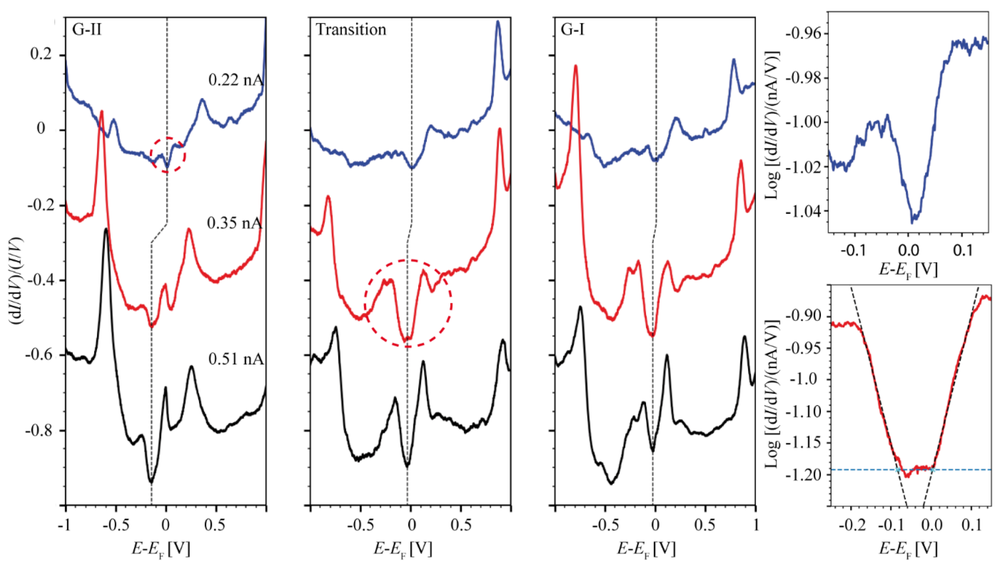
Distinct differences of the graphene structure obtained for the two regimes.

- **G-I** reveals a **super lattice** structure.
- **Honeycomb-type** atomic arrangement of graphene is resolved for both regimes.
- **No** lattice defects are observed.

STM Image



STS measurements



Dirac cone on nearly free standing graphene (G-II) ⇨ slight p-type doping.

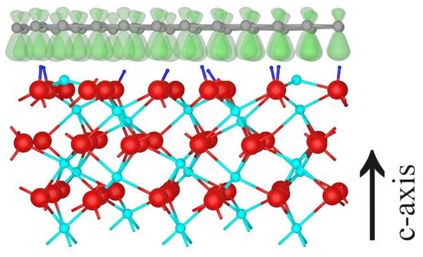
Band gap opening on the weakly bonded graphene (G-I).

G-II curves show a clear shift of the Dirac cone with the W-tip approaching
⇨ Surface states of nearly free-standing graphene are easily modified
G-I curves, in contrast, show a small Dirac cone shift and a band gap opening
⇨ Surface states of graphene weakly bonded to sapphire are less sensitive.

Summary

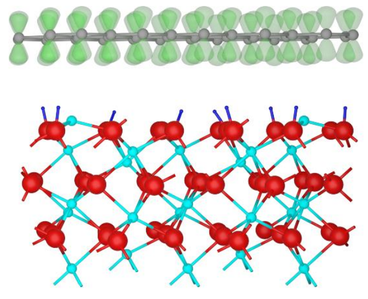
Multi-sale analysis of homogeneous wafer-scale SLG on α-Al_2O_3 (0001) grown by CVD with a low defect density, slight p-type doping and high carrier mobility (≈ 1,500 cm^2/Vs) revealed **structural differences on the sub-micron to atomic scale.**

G-I



Weak electrostatic bonded graphene towards OH-terminated sapphire surface on the terraces

G-II



Nearly free-standing graphene in step edge region.

References

[1] Backes, C. *et al.*, *2D-Materials* 7, 22001/1-280 (2020).
[2] Mishra, N. *et al.*, *Small* 15, 1904906/1-8 (2019).
[3] Samples provided by M. Heuken, AIXTRON SE.

NEUROTEC
Project Nos. 16ES1133K/1134
SPONSORED BY THE
Federal Ministry of Education and Research