Science Day PhD thesis presentation

Krzysztof Gajewski

21.01.2025

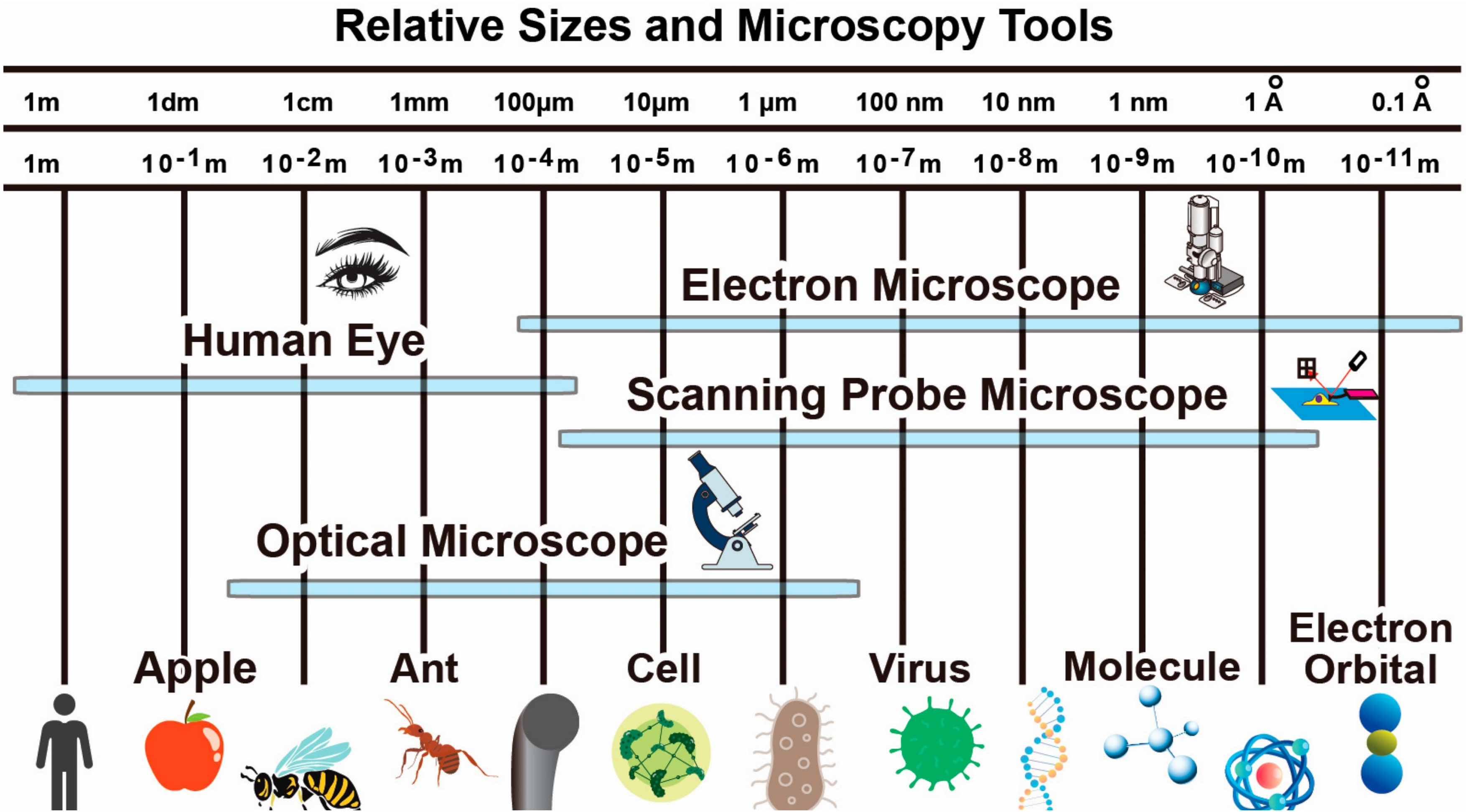
Agenda

1. Who am I?
2. What did I do?
3. Summary

NOKIA

Who am I?

- MN, **Network Management**
- Nokian since 05.2020 as a SW developer
- Since 11.2022 as a SW archtiect
- Involved in 3 projects



F. Xia, K. Youcef-Toumi, Biosensors 2022, 12(12), 1116

PL: Grafenowe przetworniki nanoelektromechaniczne

EN: Graphene nanoelectromechanical systems

Wrocław University of Science and Technology

HR EXCELLENCE IN RESEARCH

Supervisor prof. dr hab. inż. Teodor Gotszalk

This work was supported by the Foundation for Polish Science TEAM Programme “High-resolution force and mass metrology using MEMS/NEMS devices – FoMaMet” (Grant No. TEAM/2012-9/3), co-financed by the European Regional Development Fund resources within the framework of Operational Program Innovative Economy

This work was supported by the National Science Centre, Poland by the PRELUDIUM 9 programme "Investigations of the properties of graphene nanoelectromechanical systems with the use of scanning probe microscopy and Raman spectroscopy" (grant Nr 2015/17/N/ST7/03850)

Some of presented works were supported by the FP7 project STREP NanoHeat (Nr 318625) „MultidomaiN plAtform for iNtegrated MOre-tHan-MoorE/Beyond CMOS systems charActerisation & diagnosTics.” financed using the european funds.

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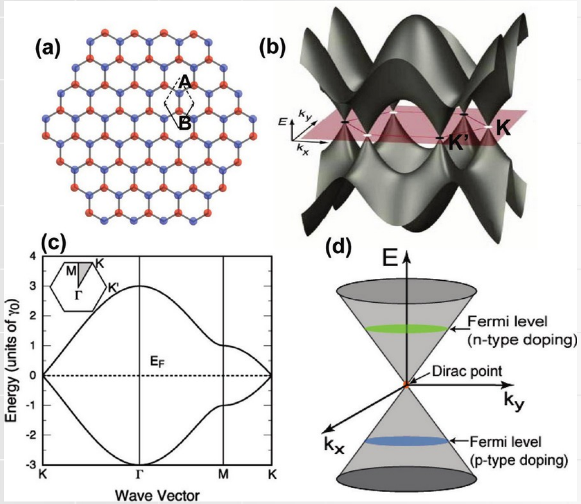
Graphene

- Carbon atoms connected by in-plane strength sp^2 bonds
- Free π electrons
- Lattice constants a_{AB} = 1.41 Å, a_{AA} = 2.45 Å
- Electron velocity $v_F \sim 10^6\ ms^{-1}$
- Electron mobility ~ 200 000 $cm^2V^{-1}s^{-1}$
- Graphene ambipolarity – in dependence of external electric field it can be „n” or „p” type
- Thermal conductivity 3080 – 5150 W/mK



P. Avouris, Nano Lett. 2010,10; 4285–94.

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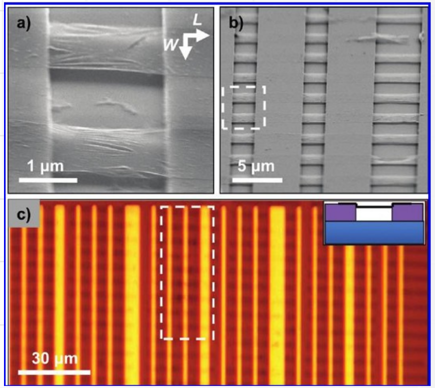
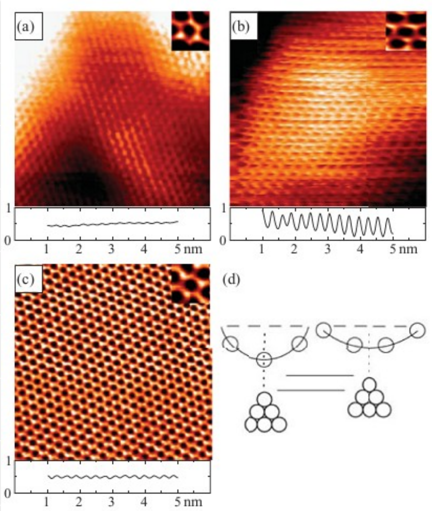
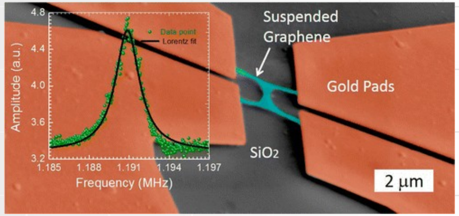
Graphene and GNEMS



Zande AMVD, et al., *Nano letters* 2010, 10 (12), 4869–73.

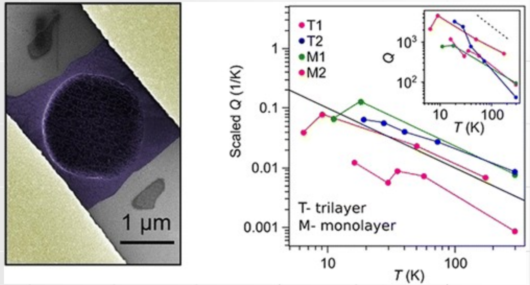


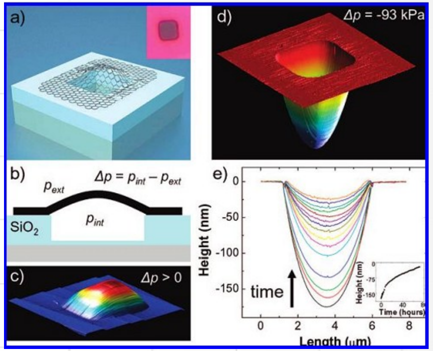
Xu P, et al., *PRB* 2012, *85*(12): 121406(R).



M. Kumar, et al., *Nano Lett.*, 2015, 15 (4), 2562–2567

T. Miao, et. al, *Nano Lett.*, 2014, 14 (6), 2982–2987





Bunch JS, et al., Nano Lett. 2008, 8 (8):2458-62.

The main goal of the thesis

- Development of methods and techniques for graphene nanoelectromechanical systems investigation using microscopic and spectroscopic technologies
- The main focus was put on scanning probe microscopy and Raman spectroscopy

The main goal could be achieved by:

Project and GNEMS preparation

Scanning tunneling microscope preparation which will be able to measure GNEMS

Atomic force microscopy techniques adaptation for GNEMS

GNEMS investigations

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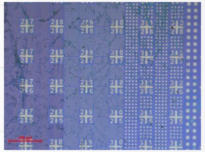
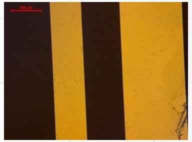
Cooperation during PhD

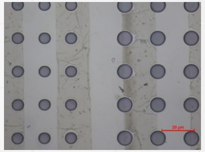
NPL National Physical Laboratory



Imperial College London

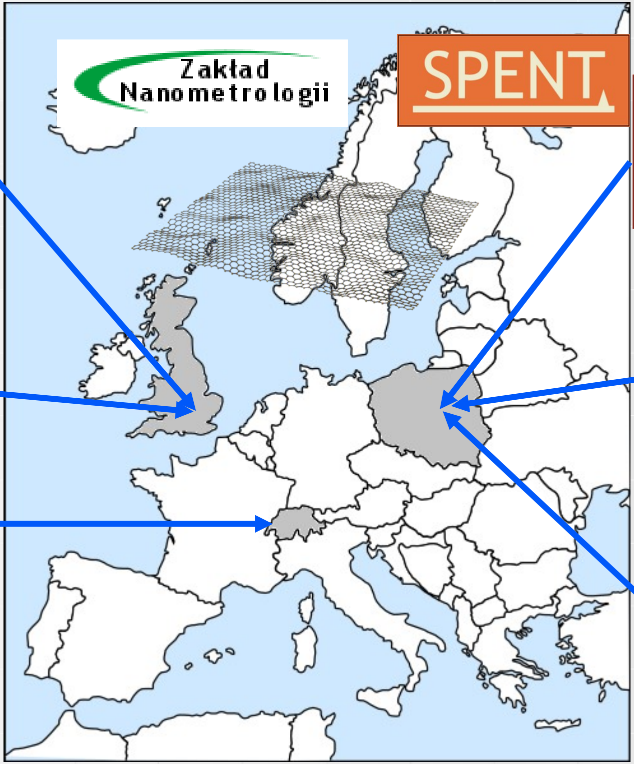
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE





Zakład Nanometrologii

SPENT



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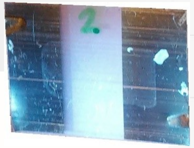
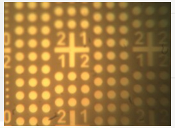
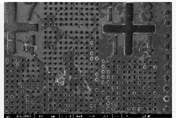


Politechnika Łódzka

ITE

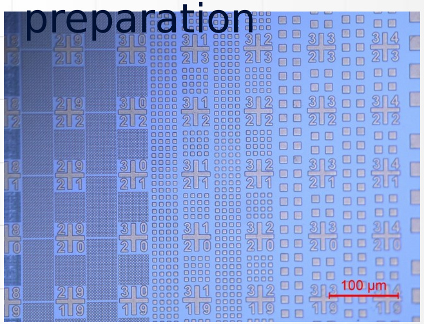


ITME



Typical GNEMS sample processing

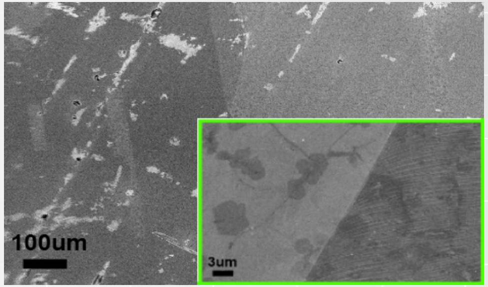
Substrate preparation



Gajewski, K. R., et al., Proc. SPIE 8902, Electron Technology Conference 2013, 89020G (July 25, 2013).

- 300 nm SiO_2 / Si.
- Apply photoresist
- Photolitography
- Photoresist removal
- SiO_2 etching

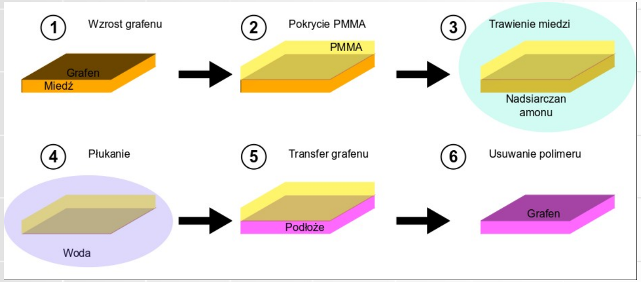
Graphene growth



Goniszewski, S.,..., **K. Gajewski,** et al., IET Circuits, Devices & Systems, 2015, 9, (6), p. 420-427.

- Growth on copper foil
- Low pressure (110 mbar), high temperature (1035 ˚C).
- Methane as a carbon source
- Hydrogen used to minimize oxidation

Graphene transfer



- Graphene covered by PMMA
- Graphene etching from the bottom side using nitric acid.
- Copper etching using ammonium persulfate.
- Graphene cleaning.
- Transfer.
- PMMA etching in dichloromethane
- Annealing (350 ˚C ,10 h, P≈ 2 mbar, hydrogen flow100 sccm

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The main goal could be achieved by:

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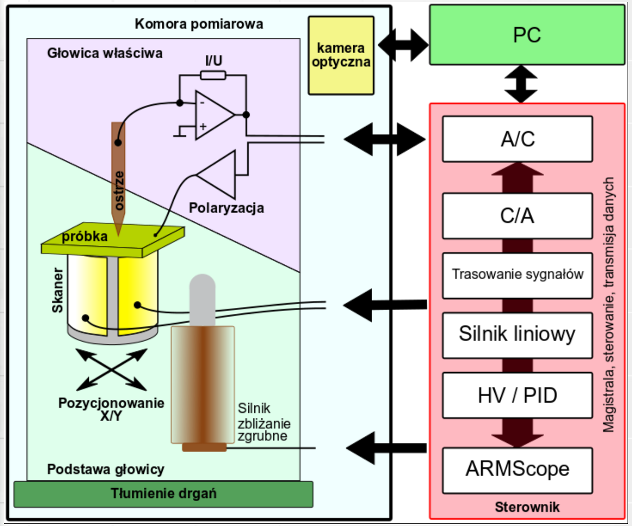
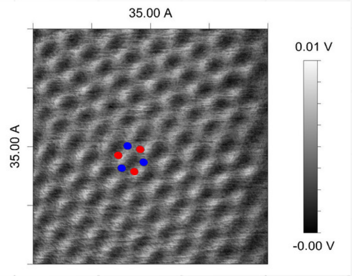
Atomic force microscopy techniques adaptation for GNEMS

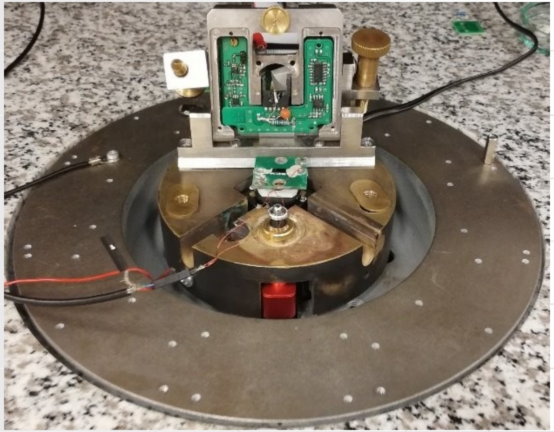
GNEMS investigations

STM capable to investigate GNE





- Movable tip
- Movable sample
- Sample movement in X/Y axis
- Constant current and constant height modes
- STM related modes introduced:
  - STP
  - z-U_{bias} spectroscopy



Gajewski, K., et al.., Microel. Eng., 212 2019, 1-8

Gajewski, K., et al., MST, 28(3) 2017, 034012

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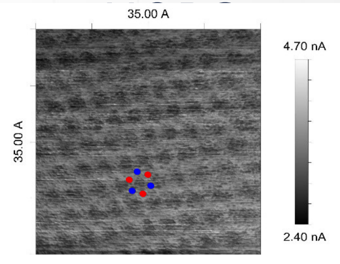
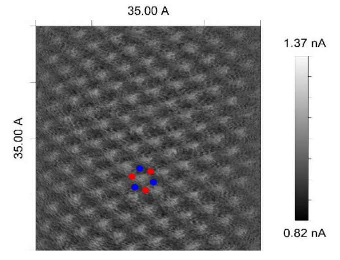
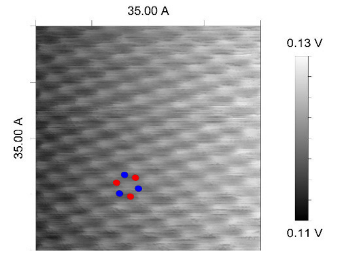
Introduced measurement modes

Constant height -



Constant current -

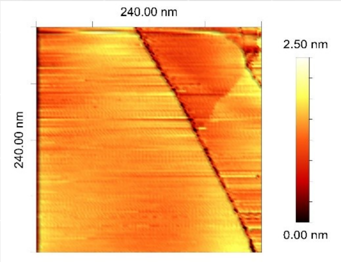




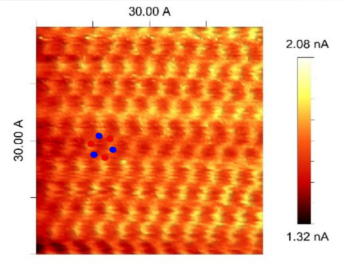
Tunneling current
U_{PID}

HOPG in the atomic scale (35 Å x 35 Å), I_t = 1 nA, U_{bias} = 100 mV

AC–STM - HOPG

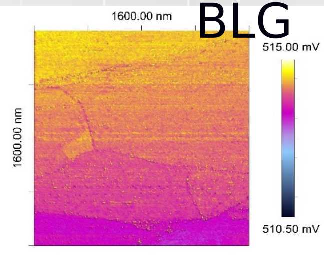


Topography

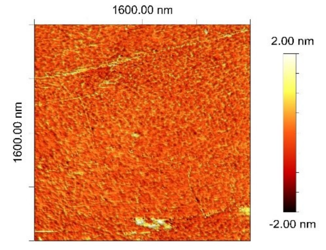


Tunneling current

STP - EPFL BLG



Potential distribution



Topography

STP, 1600 nm x 1600 nm
I_{AC} = 1 nA, U_{AC} = 30 mV, f_{AC} = 30 kHz

Gajewski, K., et al., Elektronika LIV, 06, 2013, 14 - 9.

Gajewski, K., et al., Applied Surface Science, vol 510, 30 April 2020, 145504

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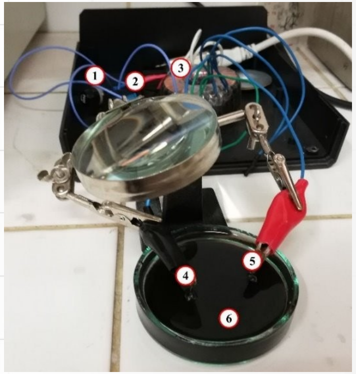
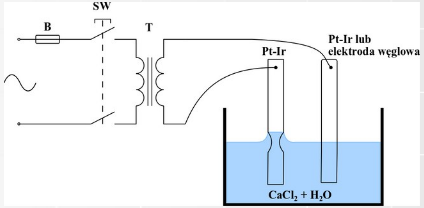
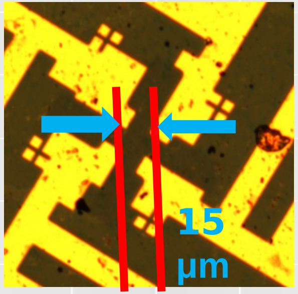
Optical observation and STM tip etching

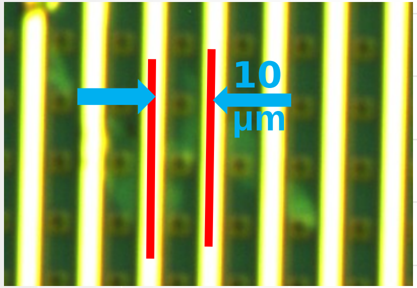
Small sample requires capability of its optical observation



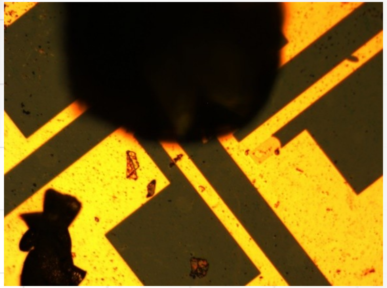




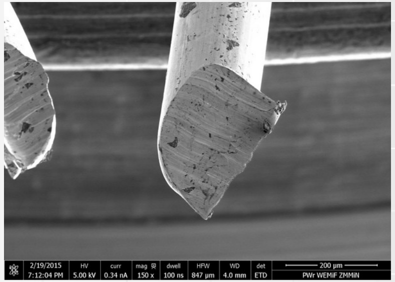
Gajewski, K., Microelectronic Engineering, 212 2019, 1-8



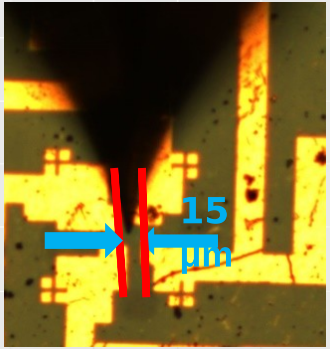
Tamulewicz, M., Kutrowska-Girzycka, J., **Gajewski, K.**, et al., Nanotechnology. 24 (30) 2019, s. 1-8.

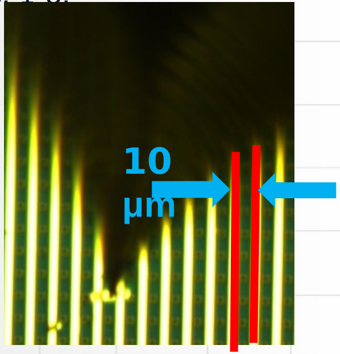


Optical camera, cutted tip



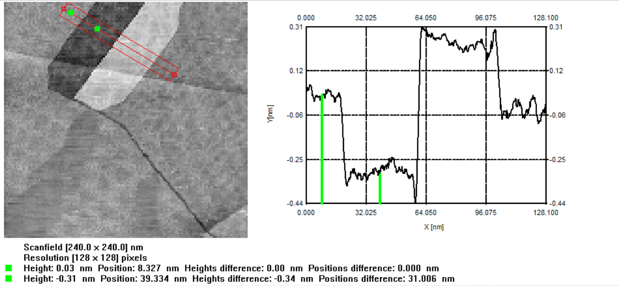
SEM





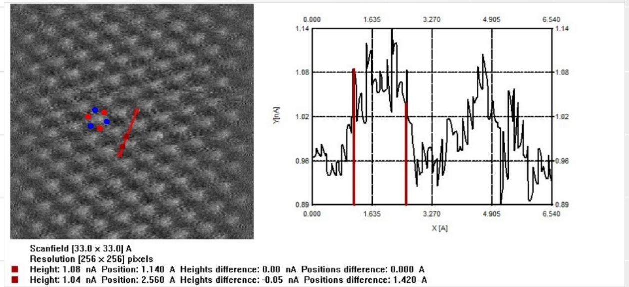
STM Microscope scaling

Z

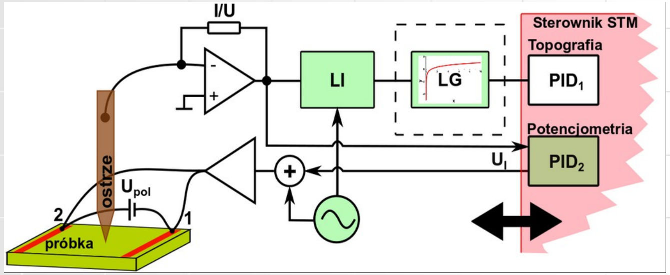


6.08 nm/V, Moiré pattern on HOPG

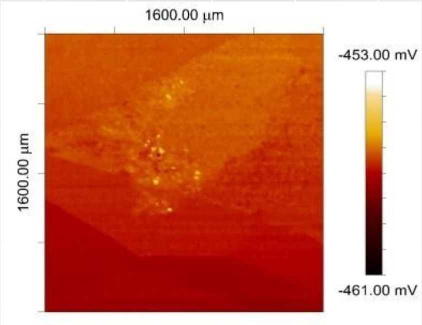
X/Y

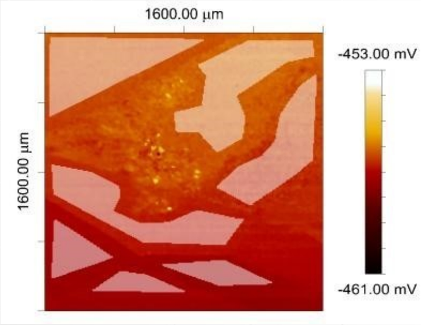


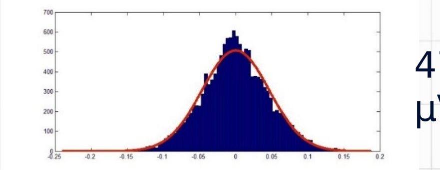
Atomic scale 33 Å x 33 Å



Minimal detectable potential, CVD graphene/Al_2O_3







47 µV

I.e. Keithley 2400, minimal error <u>> 300 µV</u>!!!

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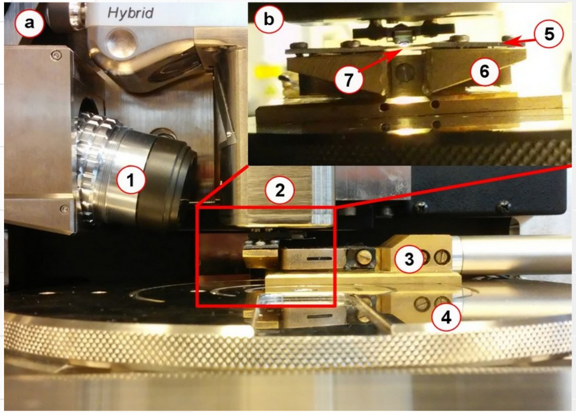
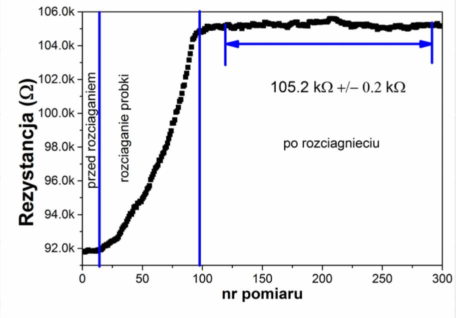
GNEMS investigations

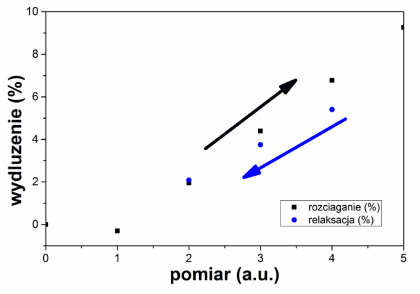
KPFM of the elongated sample – grapgene/LDPE

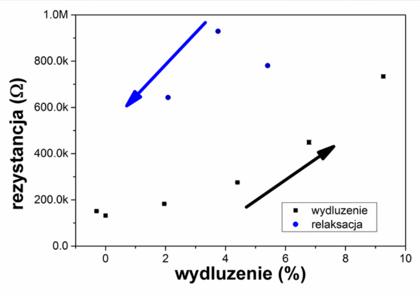




Gajewski, K., et al., Diamond and Related Materials, 82 2018, pp. 143-149

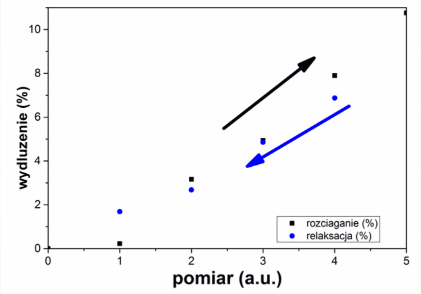
HSMG

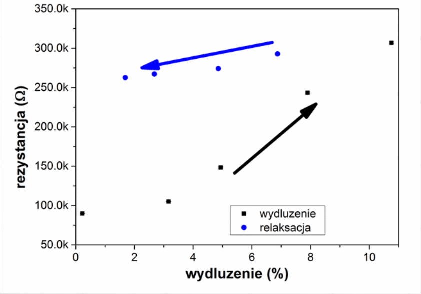




WF ~4.59 – 4.62

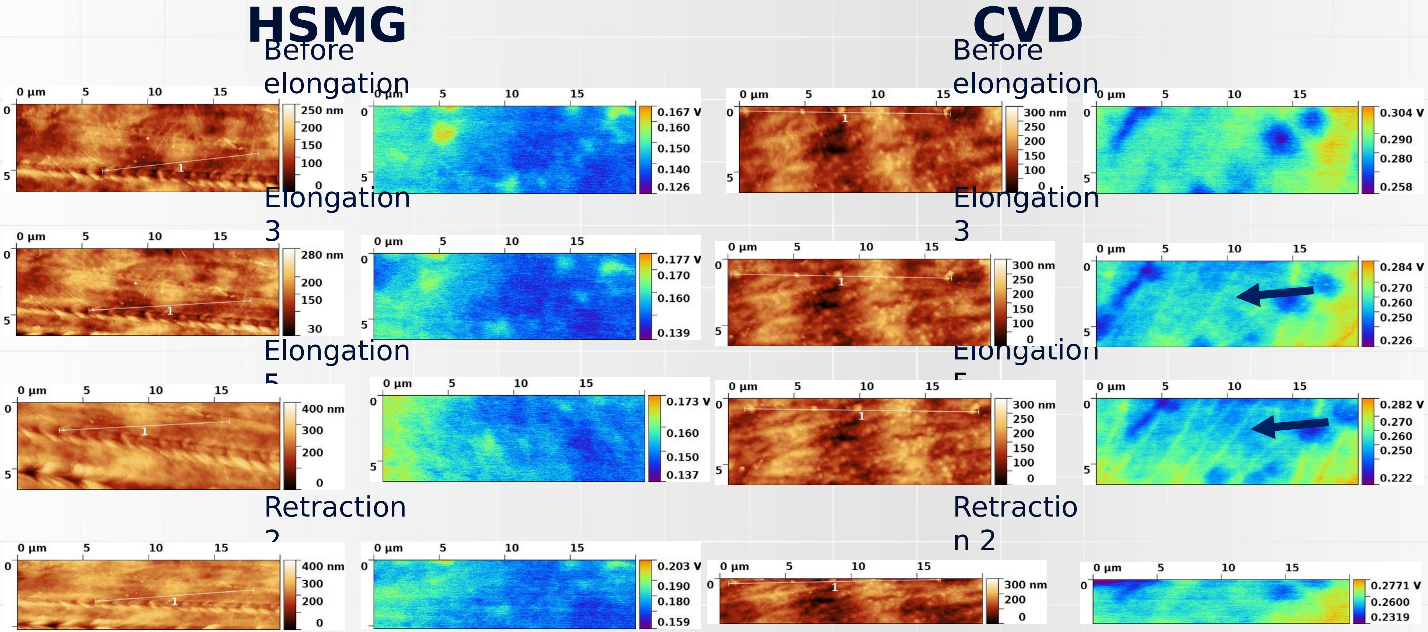
CVD





WF ~4.52 – 4.43

KPFM of the elongated sample – grapgene/LDPE



CVD graphene exhibited additional details caused by the sample elongation,

HSMG WF ~4.59 – 4.62 eV, CVD WF ~4.52 – 4.43 eV

GF ~70 (HSMG) / 30 (CVD)

Gajewski, K., et al., Diamond and Related Materials, 82 2018, 143-149

GF from publications 10 – 35

Amjadi et al., Advanced Functional, Materials, vol. 26, no. 11, pp. 1678–1698, 2016

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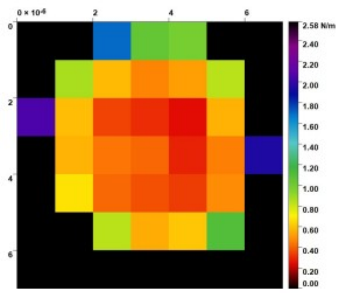
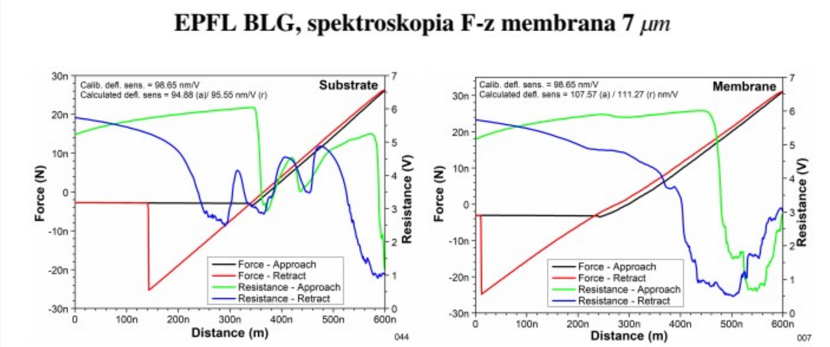
Electromechanical properties investigations using AFM



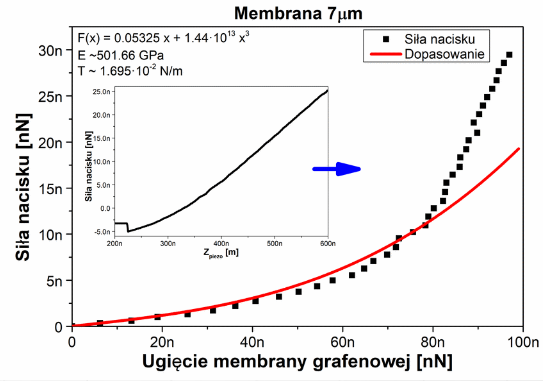
- Stiffness mapping, 7 µm membrane

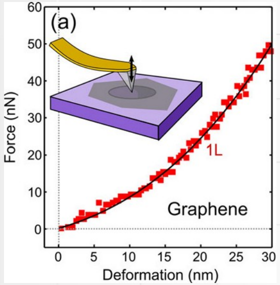
$$k_{membrana} = \frac{k_{AFM} k_{eff}}{k_{AFM} - k_{eff}}$$

Średnica [μm]	k [N/m]
2	0.309
4	0.186
7	0.218
10	0.230



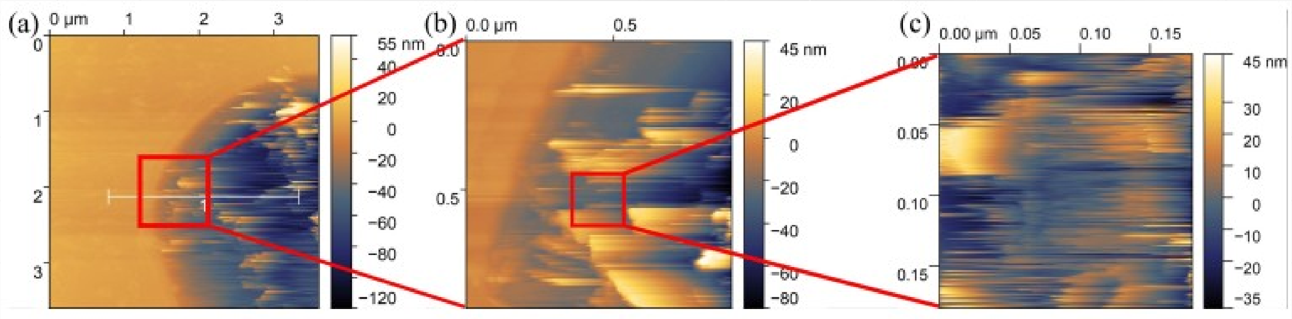
$$F = \left[\frac{4\pi t^3}{3(1-\nu^2)R^2}E + \pi T\right]\delta + \frac{tE}{q^3R^2}\delta^3$$

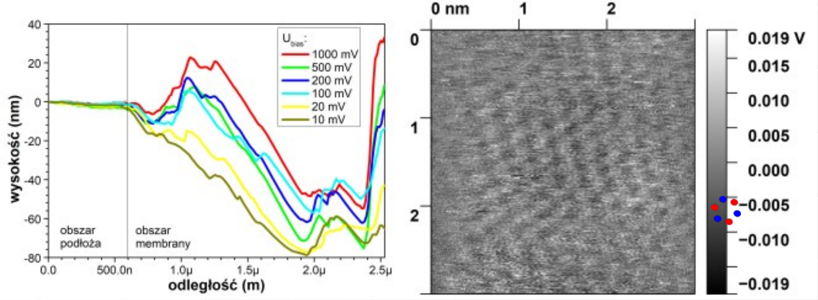




C. Lee et al., Science **321**(5887), 385–388 (2008).

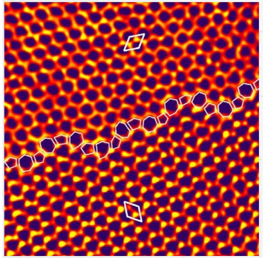
Observation of graphene membrane deformation during STM measurement.





ΔU ~ 1V → Δz ~35 nm

Alternative for TEM?

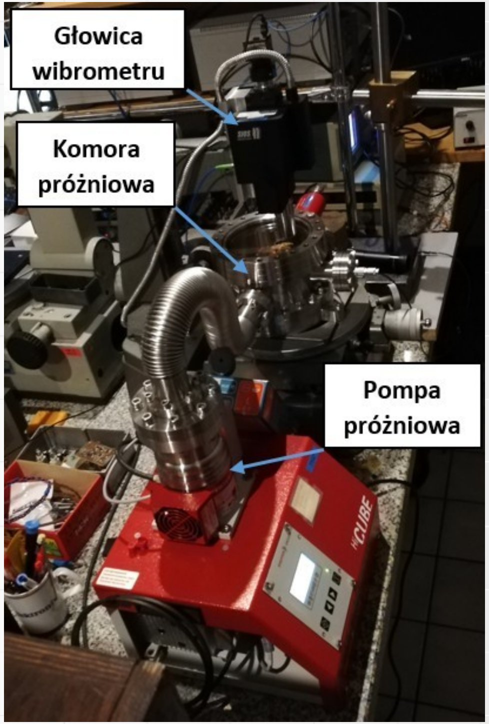


TEM

https://www.jeol.co.jp/en/products/detail/JEM-2100.html

H. Rasool, Nature Comm., vol. 4, 2013

Observation of the natural resonance of a graphene membrane – laser vibrometry



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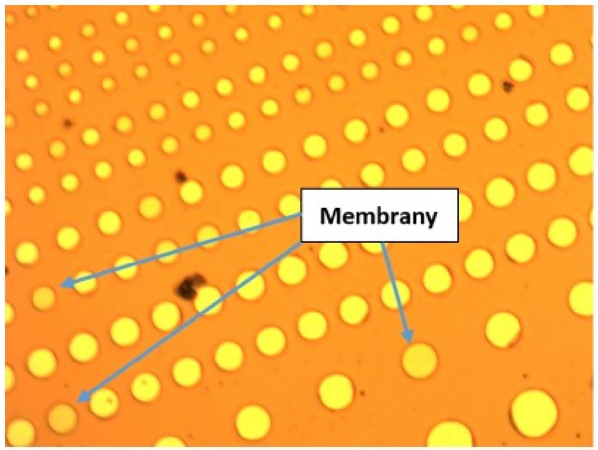


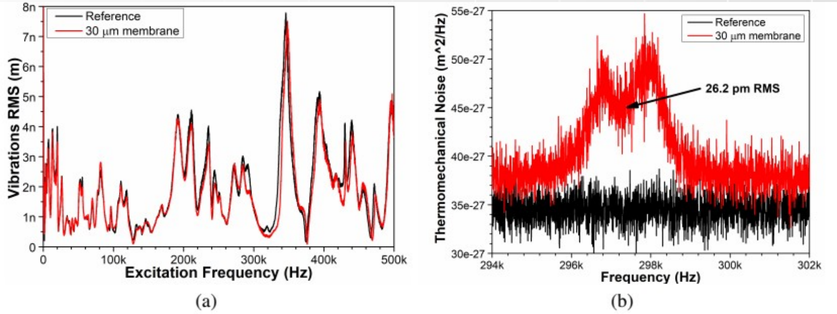
Cooperation with mgr inż. Piotr Kunicki

Observation of the natural resonance of a graphene membrane – laser vibrometry

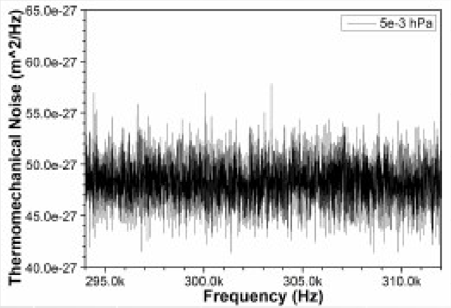
Measurements in vacuum

Enforced vibrations

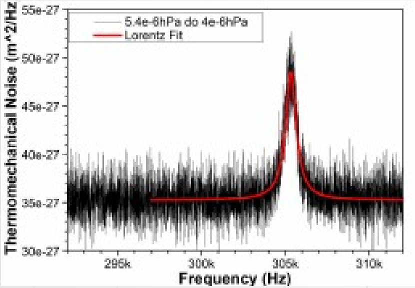
Natural vibration



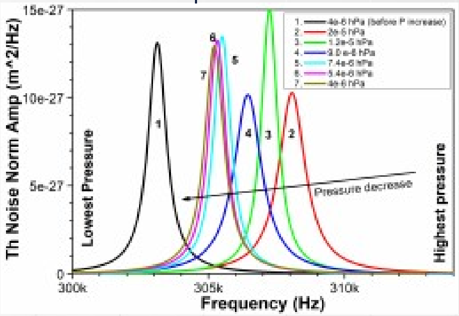
5e-1 Pa



5e-4 Pa



$f_r = f(P)$



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How far it was / it from Nokia?

STRENGTH-FLAW RELATIONSHIP OF CORRODED PRISTINE SILICA STUDIED BY ATOMIC FORCE MICROSCOPY

QIAN ZHONG, DARYL INNISS, AND CHARLES R. KURKJIAN
AT&T Bell Laboratories, Murray Hill, NJ 07974

ABSTRACT

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APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 3 17 JULY 2000

Metal–insulator–semiconductor tunneling microscope: two-dimensional dopant profiling of semiconductors with conducting atomic-force microscopy

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(Received 20 March 2000; accepted for publication 24 May 2000

A method for two-dimensional carrier profiling is presented, basec
atomic-force microscope (AFM) probe tip to a semiconductor sa
taken during the AFM scan on a cross-sectioned sample consisting
results show a clear dependence of the current–voltage characteri
and different behavior for *n*-and *p*-type InP. Modeling of the data
a quantitative tool for high-resolution two-dimensional dopant
Institute of Physics. [S0003-6951(00)03329-5]

Scanning capacitance microscopy imaging of silicon metal-oxide-semiconductor field effect transistors*

R. N. Kleiman,[a)] M. L. O'Malley, F. H. Baumann, J. P. Garno, and G. L. Timp
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

(Received 17 January 2000; accepted 31 May 2000)

We have studied cross-sectioned *n*- and *p*-metal-oxide-semiconductor field effect transistors with gate lengths approaching 60 nm using a scanning capacitance microscope (SCM). In a homogeneous semiconductor, the SCM measures the depletion length, determining the dopant concentration. When imaging a real device there is an interaction between the probe tip and the built-in depletion of the *p*-*n* junction. With the help of a device simulator, we can understand the relation between the SCM images and the position of the *p*-*n* junction, making the SCM a quantitative tool for junction delineation and direct measurement of the electrical channel length. © *2000 American Vacuum Society.* [S0734-211X(00)08604-2]

Summary

PhD thesis presented (just extract)

Wants more?

https://dbc.wroc.pl/dlibra/publication/141090/edition/72968

NOKIA