UNIVERSITÀ DI PISA

A calorimetric study of hydrogen storage on graphene functionalized with Titanium

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Laurea Magistrale in Fisica

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Outline

Introduction

- Hydrogen as an energy carrier
- Graphene for hydrogen storage

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- Thermometer structure
- Calorimetric method
- Calibration procedure
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- Detection of the temperature increase
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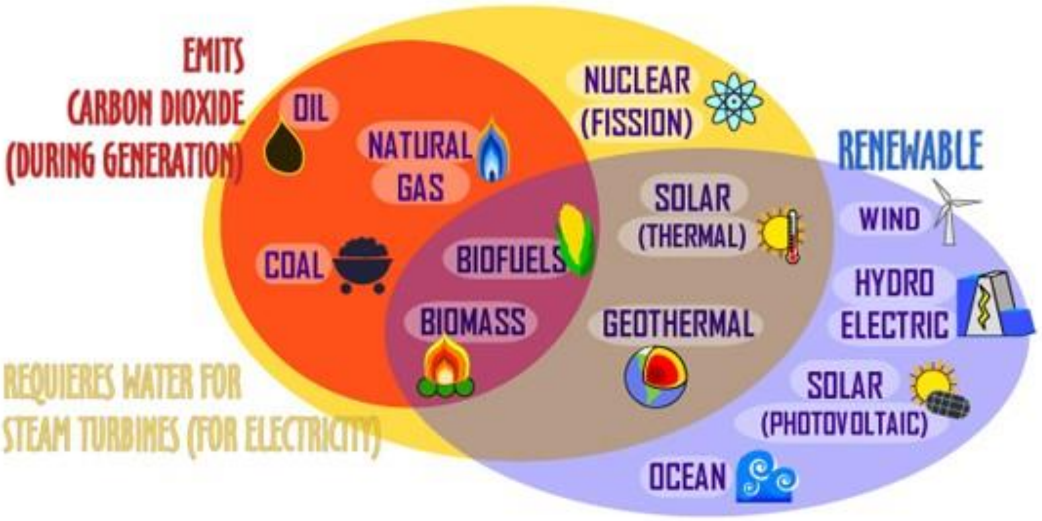
Conclusions & Outlook

Energy sources

Energy can be produced from:

- non-renewable sources (oil, coal, gas, etc.)
- renewable sources (sun, water, wind, etc.)



Energy carriers

For a complete energy distribution, we need to store it via energy sources/carriers:

- fossil fuels (natural gas, oil derivatives, and coal)
- electrochemical carriers (batteries)
- hydrogen

Hydrogen as a fuel

The advantages of H as a fuel are:

○ high energy-to-mass ratio
○ non-toxic and «clean» (H_2O as only product)
○ unlimited resource
○ reduction in CO_2 emission
○ reduction of oil dependency

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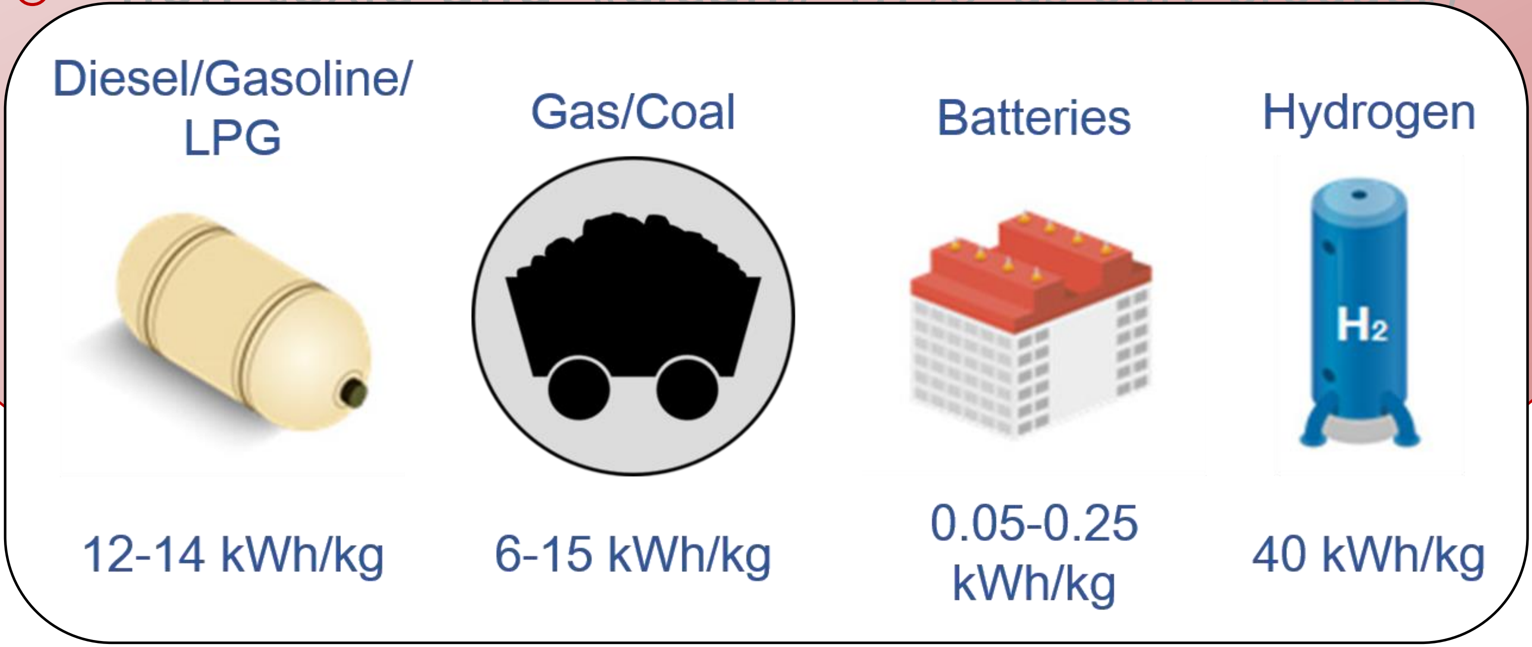

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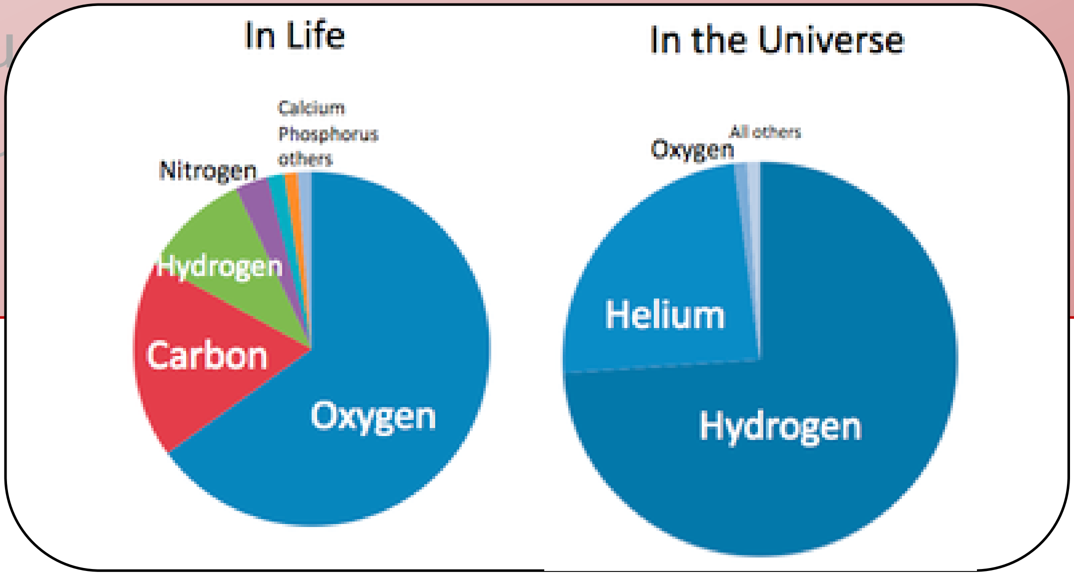

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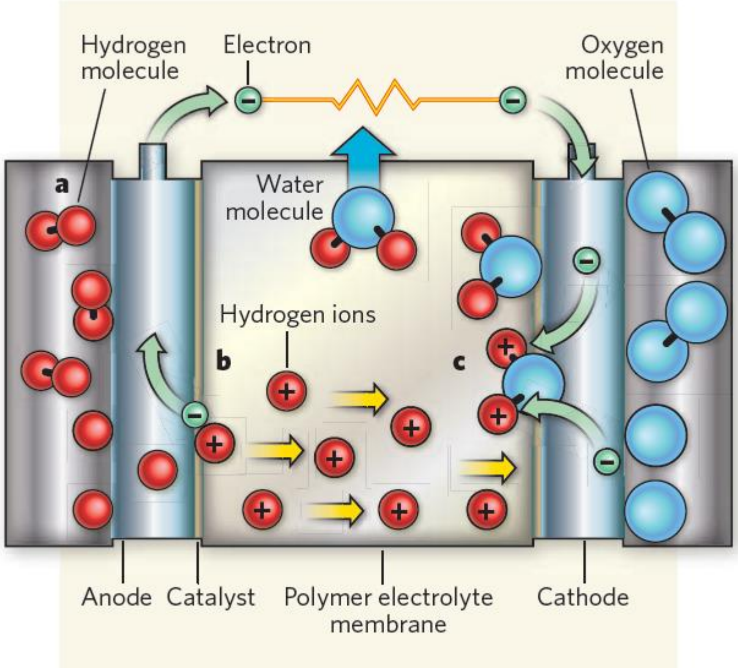
Hydrogen

Hydrogen must be produced (e.g. from the electrolysis of water) and the same amount of energy used for its production is subsequently obtained via hydrogen fuel cells.



$$2H_2 + O_2 \rightarrow 2H_2O$$

$$\Delta H = -2.96\, eV\ (\times 2)$$

Hydrogen storage

- high-pressure tanks:
  - *Volumetric Density, VD* $\sim 36\,\mathrm{kg/m^3}$
  - *Gravimetric Density, GD* $\sim 6\,\mathrm{wt.\,\%}$
  - Disadvantages: safety of pressurized cylinders, dangerous leaks.

$$P \approx 300 - 700\ \mathrm{bar}$$

Hydrogen storage

- cryogenic tanks:
  - $VD \sim 70\ \mathrm{kg/m^3}$
  - $GD \sim 3 - 10\ \mathrm{wt.\,\%}$
    (depending on the size of the container)
  - Disadvantages: boil-off losses (0.2% per day), large energy for liquefaction.

$T \approx 21\ \mathrm{K}$

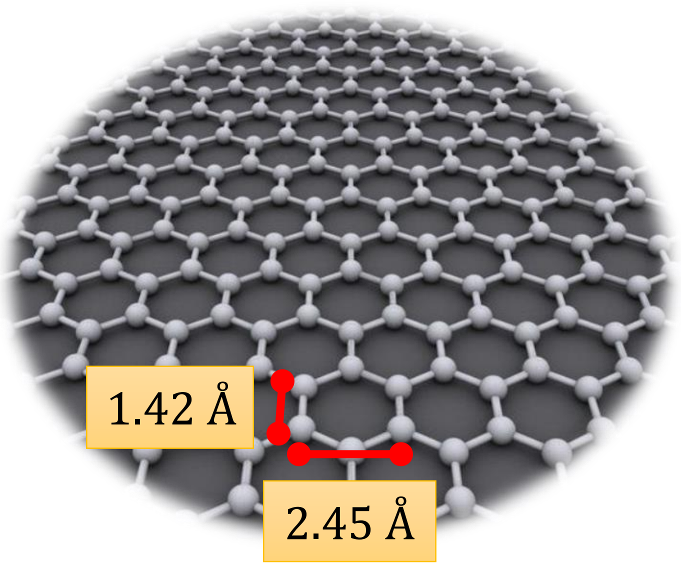
Hydrogen storage

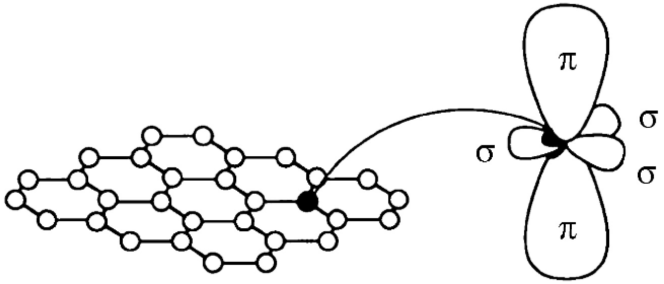
- Solid state materials:
  - *Absorption*: incorporation into the material's structure.
  - *Adsorption*: binding of atomic or molecular H on the material's surface.

Graphene has favorable physical-chemical properties for hydrogen adsorption.

Graphene

Graphene is the first 2D material, discovered in 2004. The chemical properties of its carbon atoms allow the sp^2 hybridization of the atomic orbitals, and the structure arrangement in a honeycomb geometry.





Graphene for H storage

Graphene favorable properties are:

- lightweight, robust and chemically stable
- large specific surface area ($\sim 2600\,\mathrm{m}^2/\mathrm{g}$)
- several production techniques: “top-down” or “bottom-up”
- adsorption by *physisorption* (van der Waals) or by *chemisorption* (chemical bonds).

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Graphene for H storage

Graphene favorable properties are:

- lightweight, robust and chemically stable
- large surface area ($\sim 2600\ \mathrm{m^2/g}$)
- several production techniques: "top-down"

- *physisorption*: low T or high P

$$E_b \approx (0.01 - 0.3)\ \mathrm{eV}$$
$$GD < 3.3\ \mathrm{wt\%}$$

- *chemisorption*: room/low T and atmospheric P

$$E_b \approx (1 - 1.5)\ \mathrm{eV}$$
$$GD < 8.3\ \mathrm{wt\%}$$

Functionalization of graphene

To enhance H_2 adsorption and achieve more stable and large storage capacity, graphene can be chemically decorated with metal atoms, as Li or Ti.

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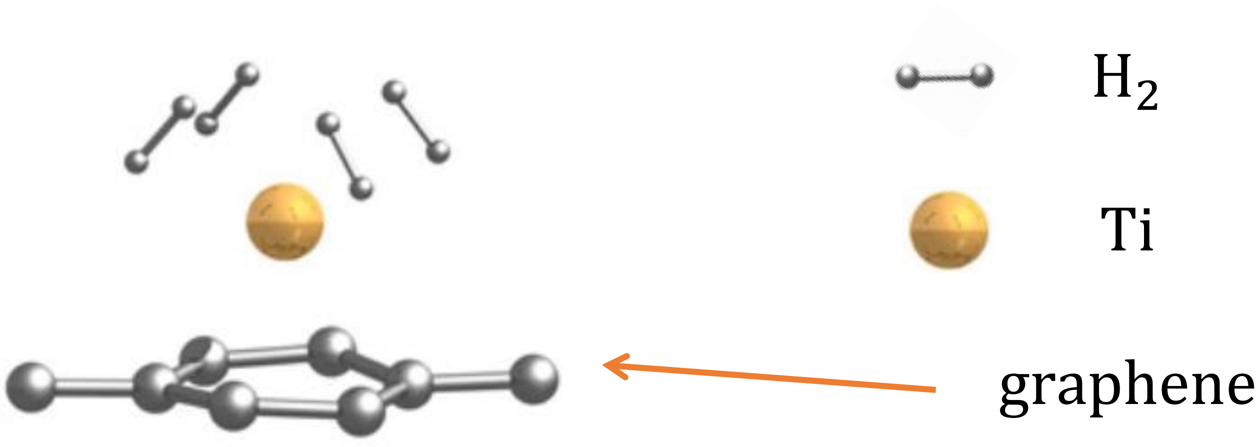
In this thesis work we functionalize the graphene surface using *titanium*, which was already theoretically and experimentally investigated.

Ti-functionalized graphene

Ti is firmly bound onto graphene surface, then up to 4 H_2 molecules are chemisorbed (at room T), with a $E_b \approx (1.1 - 1.5)$ eV.



EXPERIMENT

Idea of the Experiment

The adsorption of H_2 on Ti-decorated graphene at RT is an exothermic process.

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An original calorimetric setup has been designed, suitable for microscopic sample.

Idea of the Experiment

A simple gravimetric measurement or a standard calorimeter would allow to evaluate hydrogen storage in case of amounts of the order of grams or milligrams.

The adsorption of $1\,\mathrm{mg}$ of H_2 on monolayer graphene would need $\sim 450\,\mathrm{m}^2$ of graphene!

We want to measure $10^{-10}\,\mathrm{mol}$ ($\sim 10^{-10}\,\mathrm{g}$) of stored hydrogen, using very small samples.

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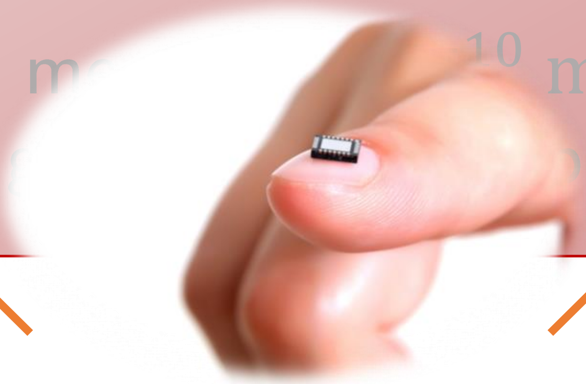
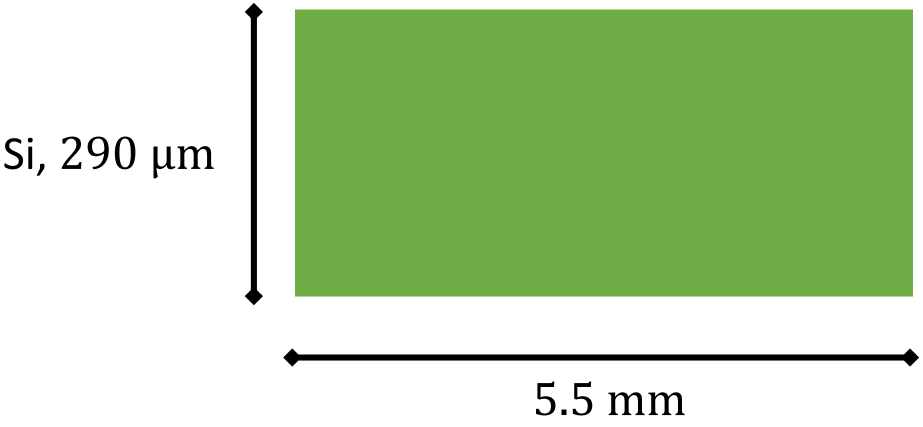


Sample's structure

- Si, physical support
- SiO_2, thermal and electrical insulator
- Ti, for the proper sticking of Au
- Au, thermometer



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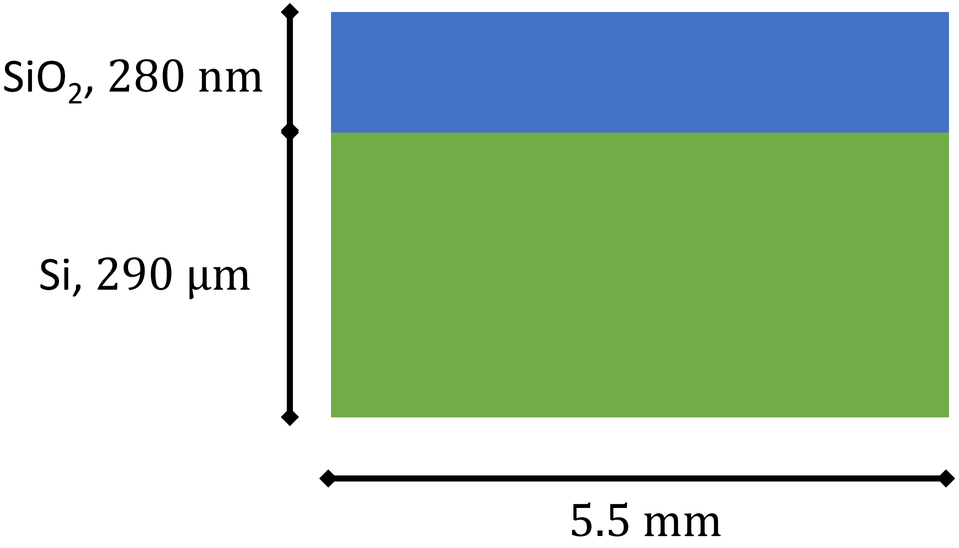

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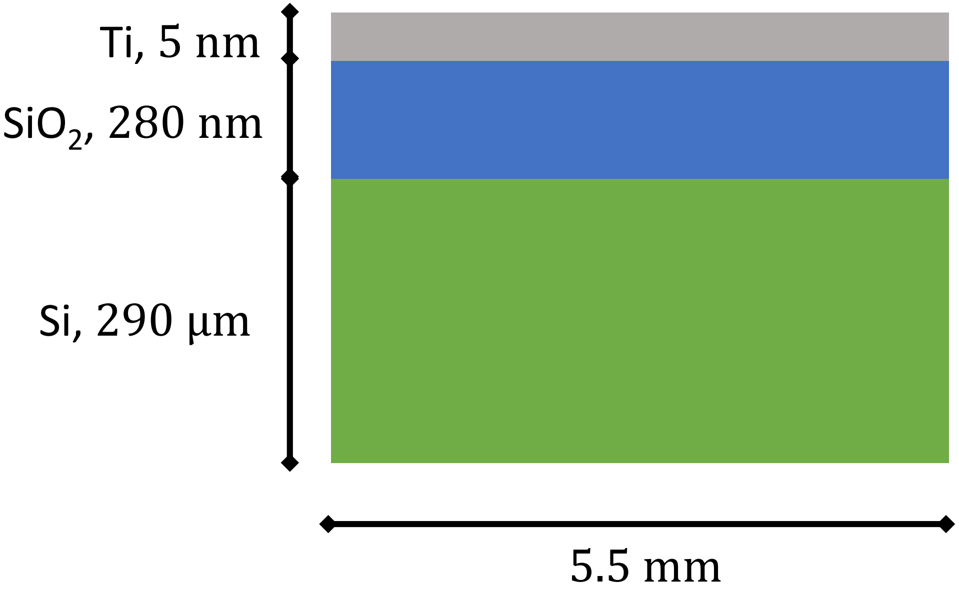

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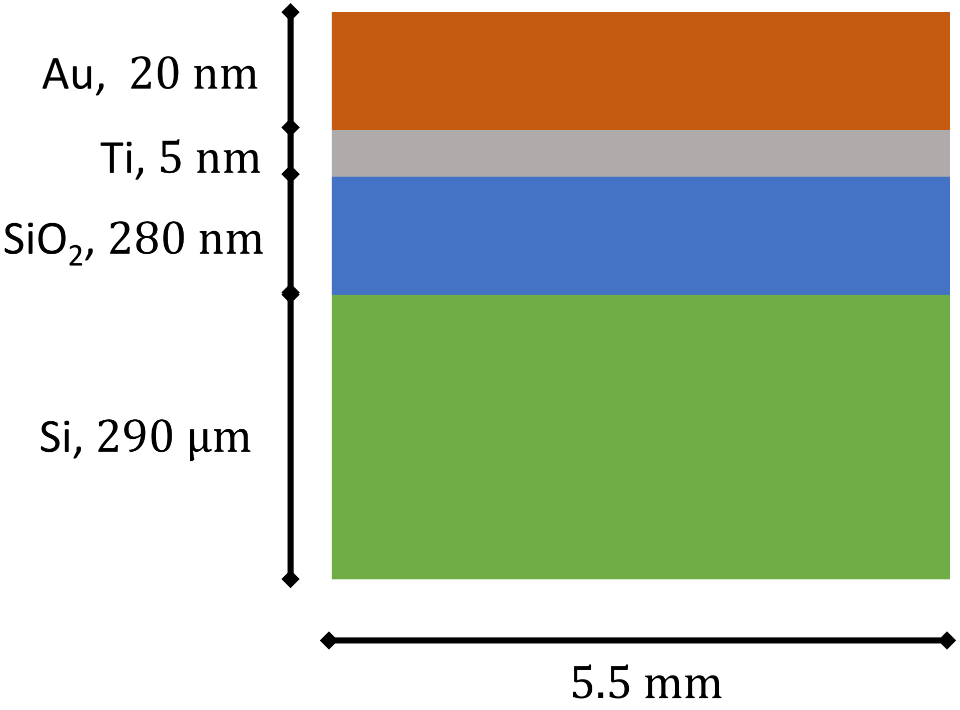

Idea of the Experiment

The idea is to utilize a thin film of gold as a thermometer, exploiting the linear relation:

$$R(T) = R_0[1 + \alpha(T - T_0)]$$

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Gold has:

- suitable resistance temperature coefficient
- good thermal and electrical conductivities
- low chemical reactivity

Thermal model

Heating power $P(t) \longrightarrow \Delta T(t)$
Thermal losses λ through the substrate

$$C\,\frac{d\Delta T(t)}{dt} = P(t) - \lambda\,\Delta T(t)$$

$$\Delta T(t) = T(t) - T_0$$

Thermal model, λ

$$P(t) = P \;\; (\text{fixed}) \longrightarrow \lambda$$

$$\Delta T(t) = T(t) - T_0 = \frac{P}{\lambda}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right]$$

$$\tau = \frac{C}{\lambda}$$

Thermal model, H_2 adsorption

$$P(t) = \frac{\delta H_r(t)}{\delta t}$$

$$\frac{\delta H_r(t)}{\delta t} = C\,\frac{\delta \Delta T(t)}{\delta t} + \lambda\,\Delta T(t)$$

H_r = total heat release

ΔT extimation

Fast thermalization of graphene + Au sensor, no losses through the substrate:

$$\Delta T \sim 5.1\ \mathrm{K}$$

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Fast thermalization of graphene + Au sensor, no losses through the substrate:

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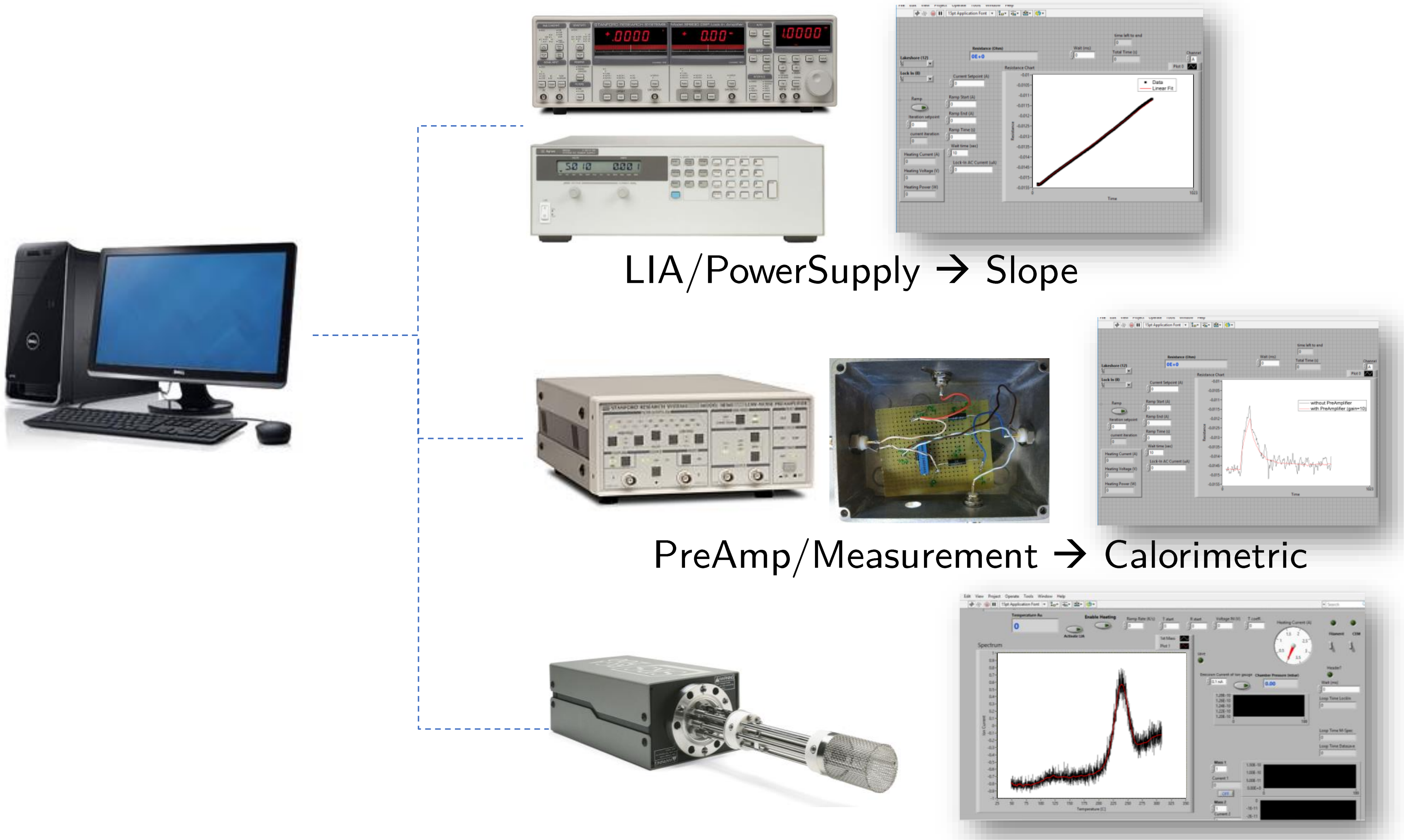
Complete thermalization of the sensor with the entire substrate:

$$\Delta T \sim 6.6 \cdot 10^{-4}\ \mathrm{K}$$

Scheme of the setup

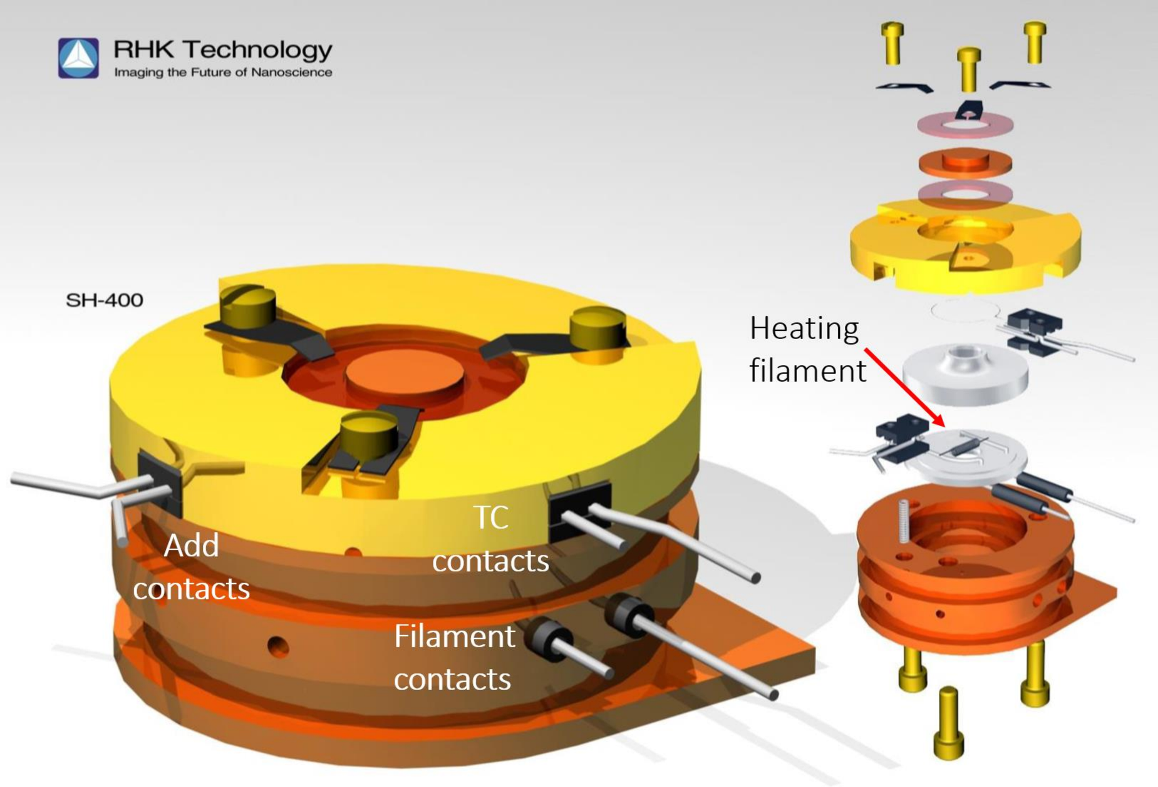


LIA/PowerSupply → Slope

PreAmp/Measurement → Calorimetric

RGA → TDS

Sample holder for UHV



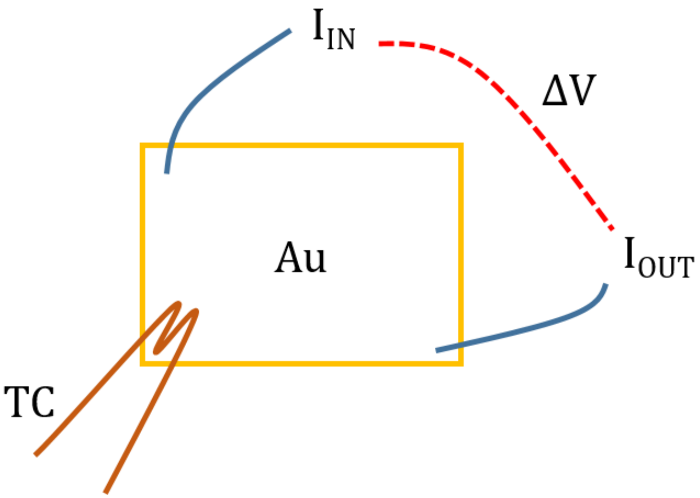
Six contacts:

- 2 → heating
- 4 → measurement

Calibration, 2-wire setup + TC

We initially calibrate the sensor using a thermocouple.

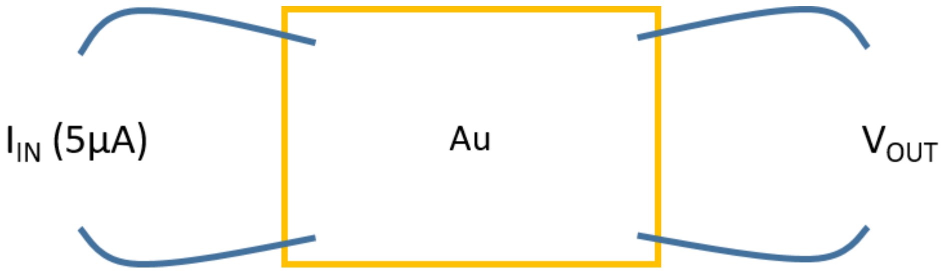
A sensing current of 5 µA flows into the sensor, and the voltage drop is measured, using the same two wires.



$$R = R_s + R_C$$

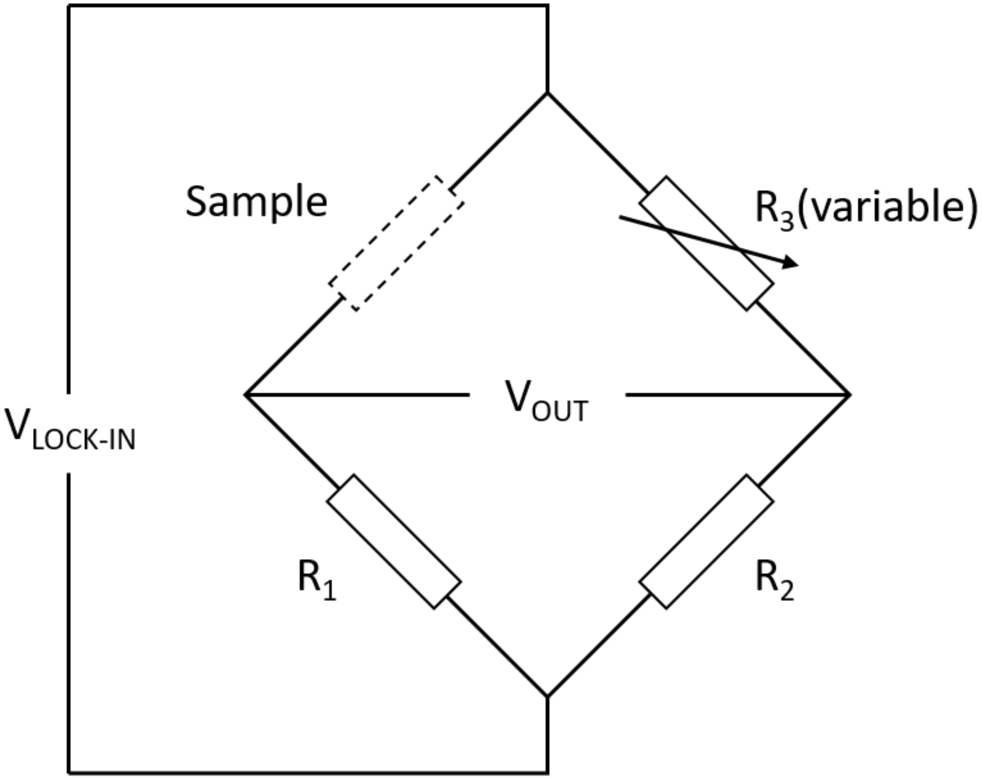
4-wire setup

To avoid the contact resistance, we pass to the 4-wire setup.



Wheatstone bridge

Finally, for increasing the sensitivity, we use a Wheatstone bridge.

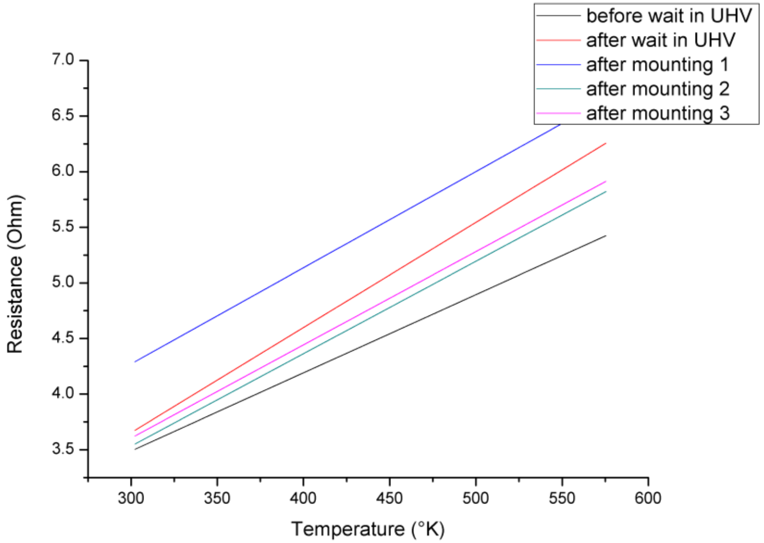


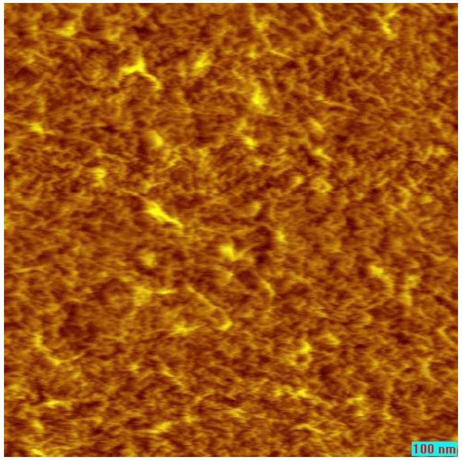
$$R_1 \approx R_2 \approx 1\mathrm{K}\Omega$$

$$R_3 \approx R_S\,(T_0)$$

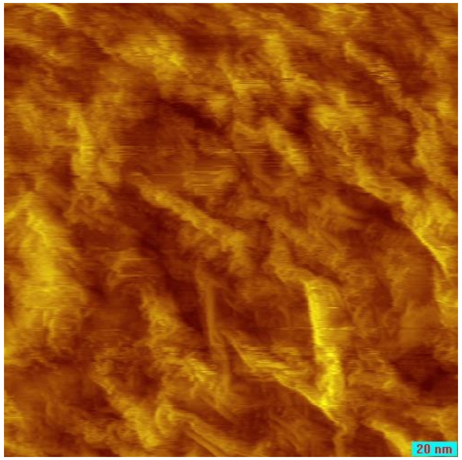
Procedure for characterization

- calibration of the thermometer (α and ρ), STM images of Au surface





1 μm × 1 μm

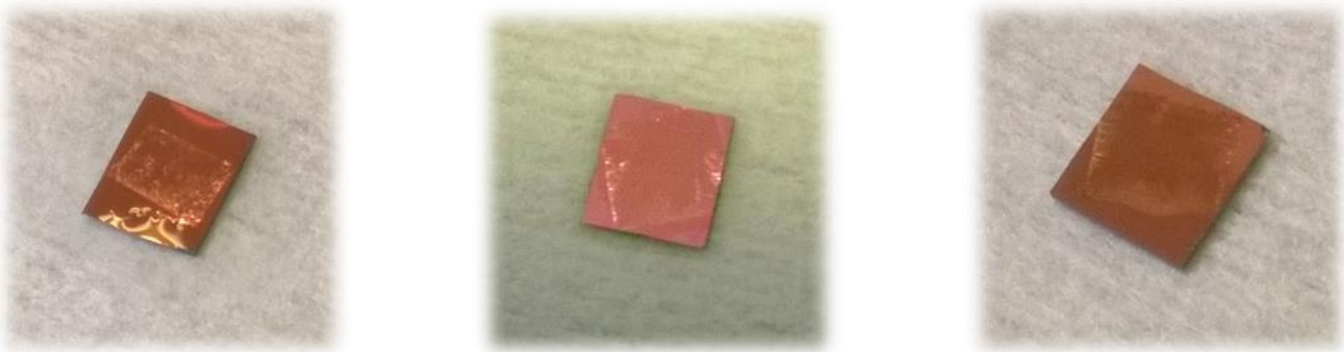


200 nm × 200 nm

Procedure for characterization

- calibration of the thermometer (α and ρ), STM images of Au surface

- transfer of monolayer graphene, calibration, Raman spectroscopy, STM on graphene



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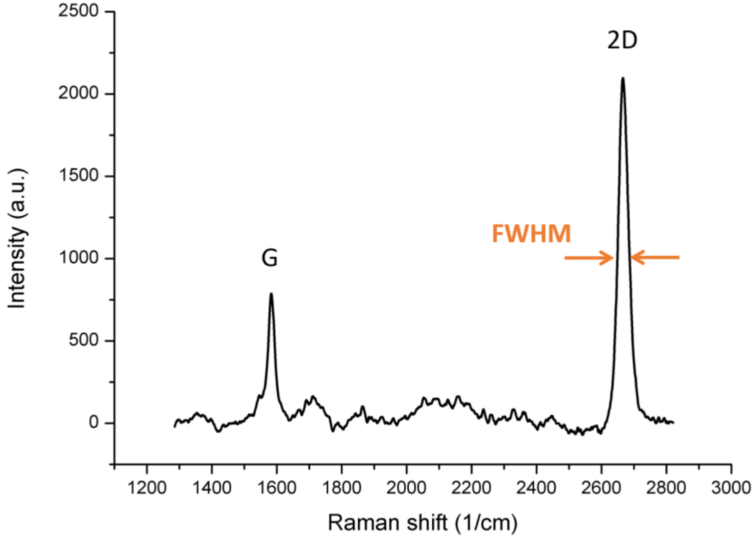
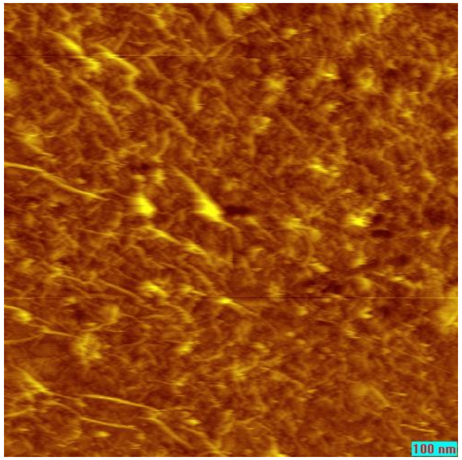
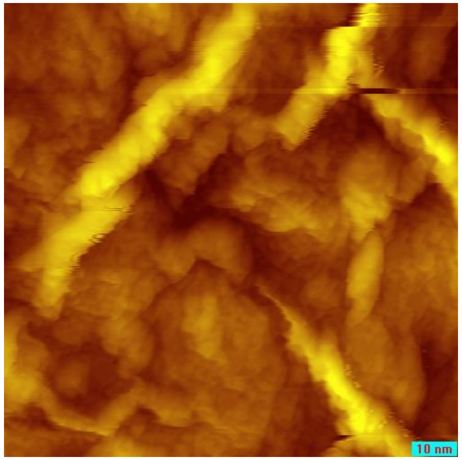




1 µm × 1 µm



100 nm × 100 nm

Procedure for characterization

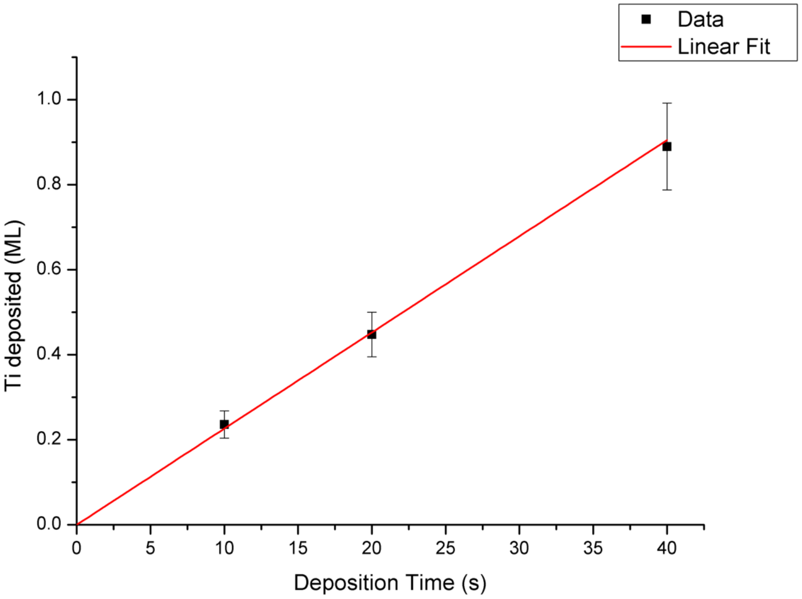
- calibration of the thermometer (α and ρ), STM images of Au surface

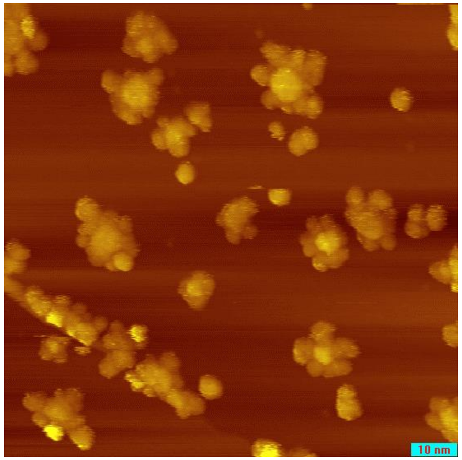
- transfer of monolayer graphene, calibration, Raman spectroscopy, STM on graphene

- calibration of Ti evaporator, evaporation of Ti, STM on deposited Ti

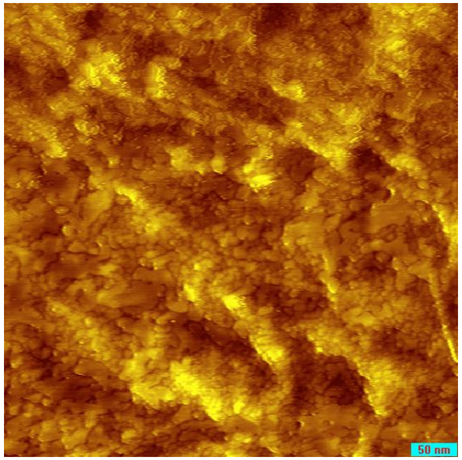
Procedure for characterization

○ calibration of Ti evaporator, evaporation of Ti, STM on deposited Ti





100 nm × 100 nm
25% coverage



500 nm × 500 nm
100% coverage

Procedure for characterization

- calibration of the thermometer (α and ρ), STM images of Au surface

- transfer of monolayer graphene, calibration, Raman spectroscopy, STM on graphene

- calibration of Ti evaporator, evaporation of Ti, STM on deposited Ti

- calculation of the heat transfer coefficient

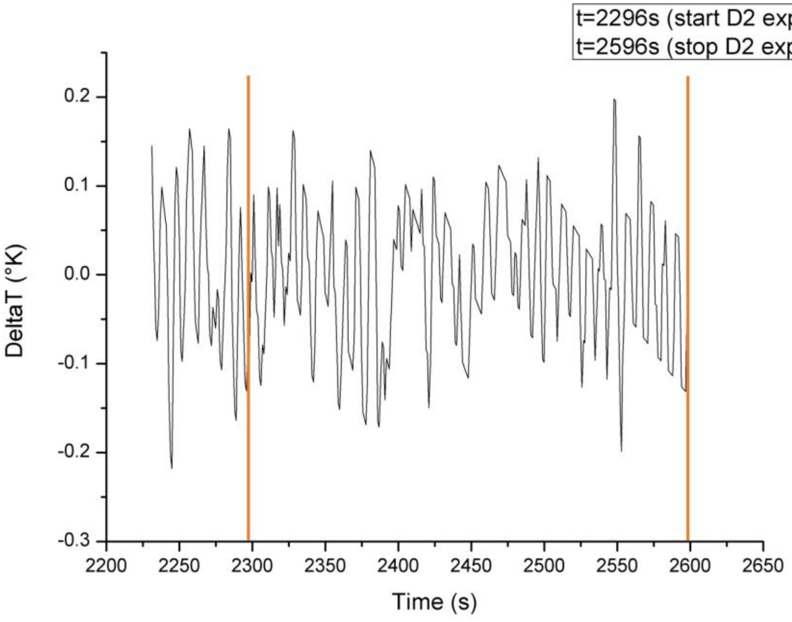
Procedure for characterization

- calibration of the thermometer (α and ρ), STM images of Au surface
- transfer of monolayer graphene, calibration, Raman spectroscopy, STM on graphene
- calibration of Ti evaporator, evaporation of Ti, STM on deposited Ti
- calculation of the heat transfer coefficient
- calibration of the RGA (for the TDS)

Measurement Procedure

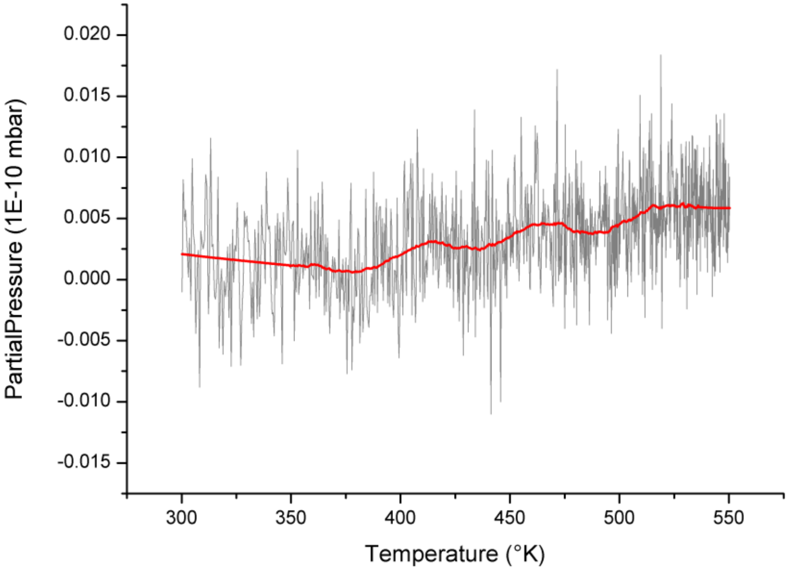
- blank measurements on Au samples (D_2 exposure, TDS)

Calorimetric measurement



No ΔT detected

TDS measurement



No desorption peak

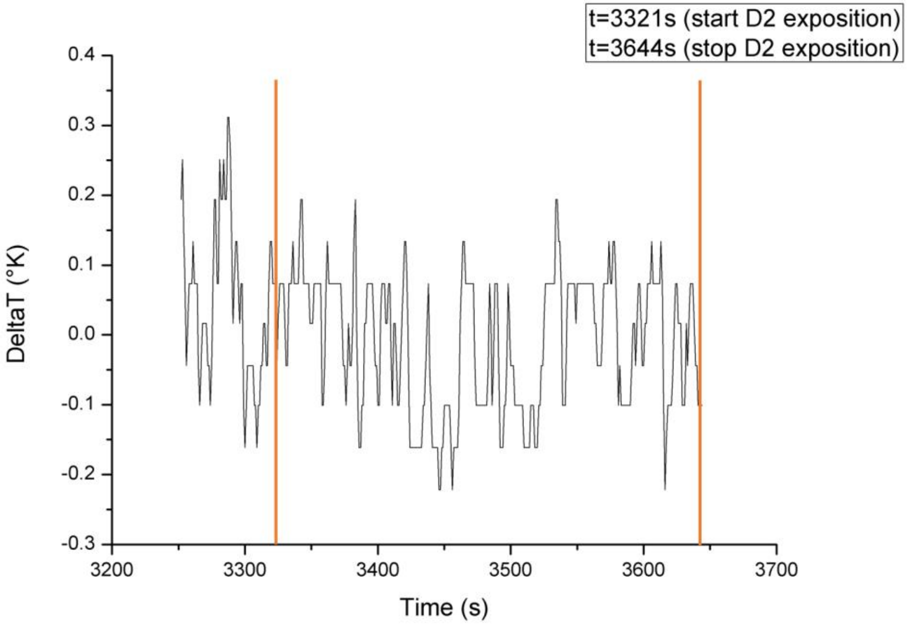
Measurement Procedure

- blank measurements on Au samples (D_2 exposure, TDS)
- blank measurements on graphene samples (D_2 exposure, TDS)

Measurement Procedure

- blank measurements on graphene samples (D_2 exposure, TDS)

Calorimetric measurement



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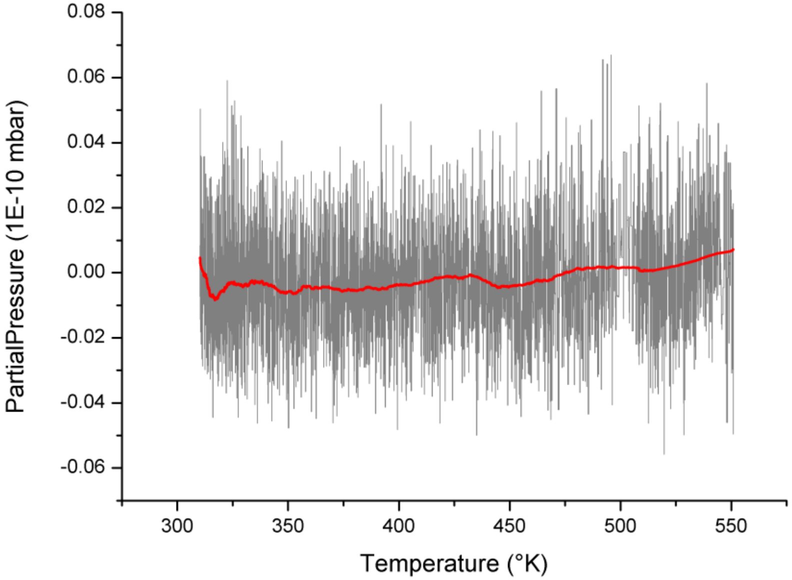
TDS measurement



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Measurement Procedure

- blank measurements on Au samples (D_2 exposure, TDS)

- blank measurements on graphene samples (D_2 exposure, TDS)

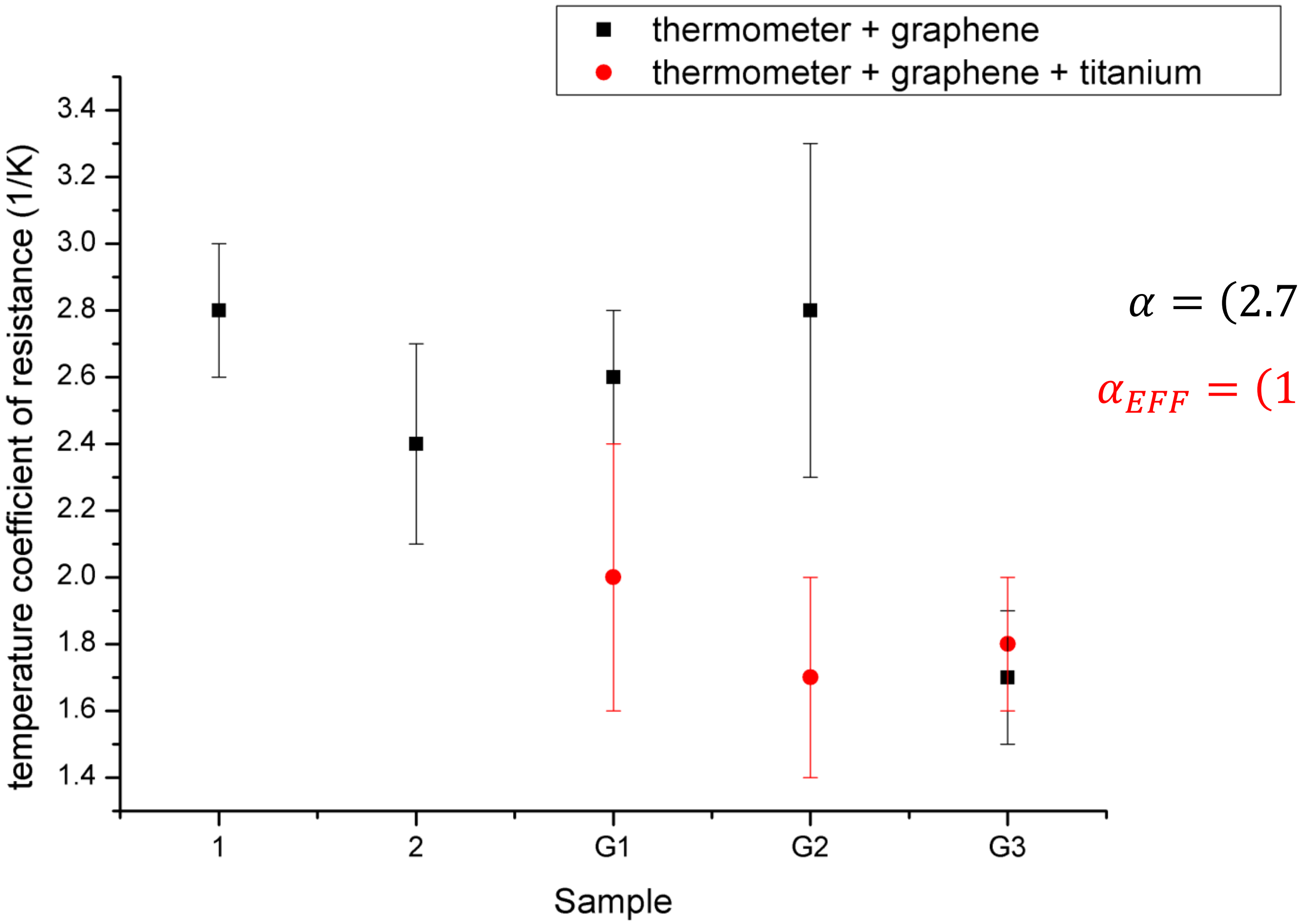
- evaporation of Ti on graphene → D_2 exposure → temperature increase, heat release

Measurement Procedure

- blank measurements on Au samples (D_2 exposure, TDS)
- blank measurements on graphene samples (D_2 exposure, TDS)
- evaporation of Ti on graphene $\longrightarrow$ D_2 exposure $\longrightarrow$ temperature increase, heat release
- TDS measurement $\longrightarrow$ desorption peak, E_b , D_2 amount, heat release

RESULTS

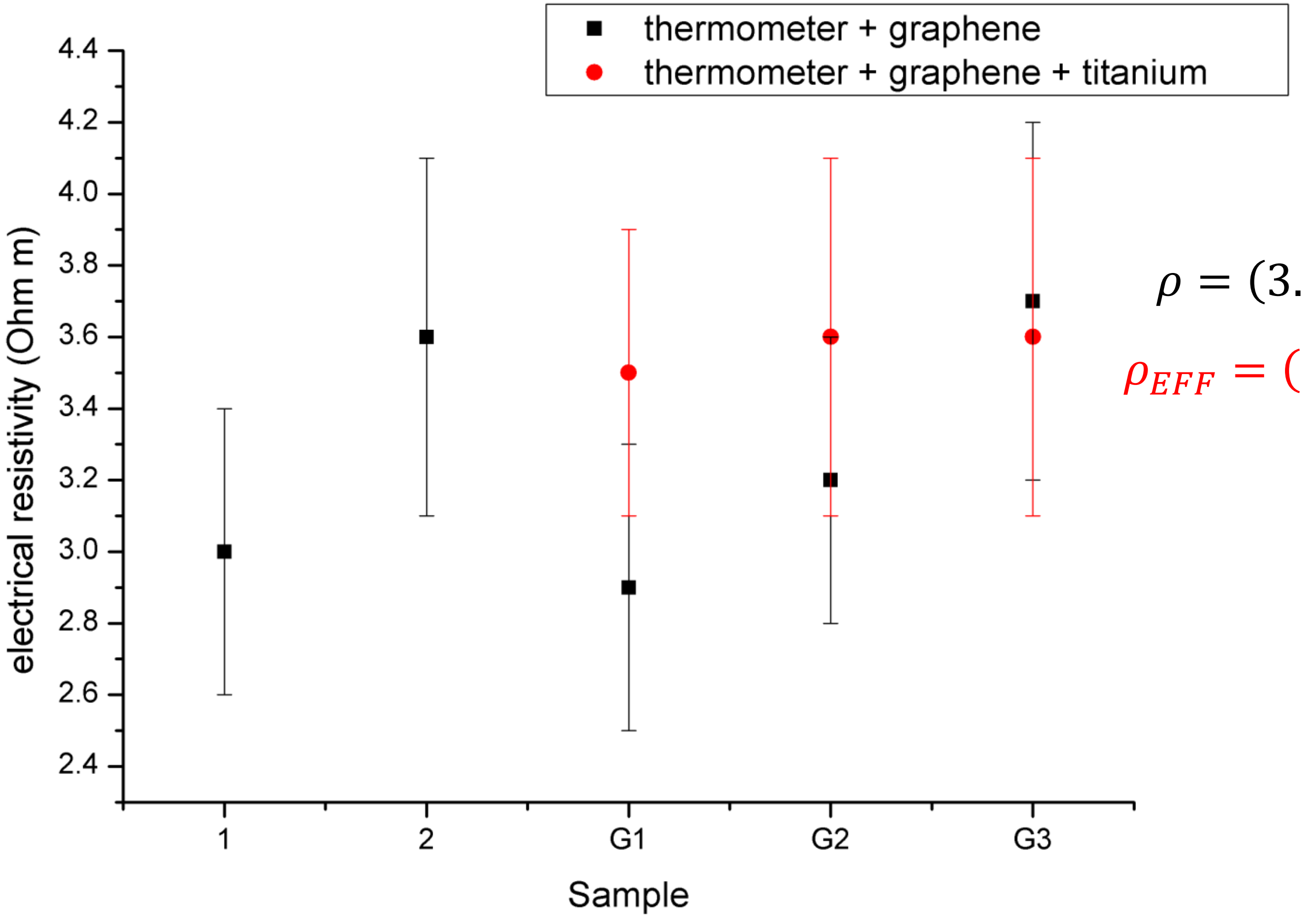
Calibration of the thermometer, α



$$\alpha = (2.7 \pm 0.1) \cdot 10^{-3}\ \mathrm{K}^{-1}$$

$$\alpha_{EFF} = (1.8 \pm 0.3) \cdot 10^{-3}\ \mathrm{K}^{-1}$$

Calibration of the thermometer, ρ

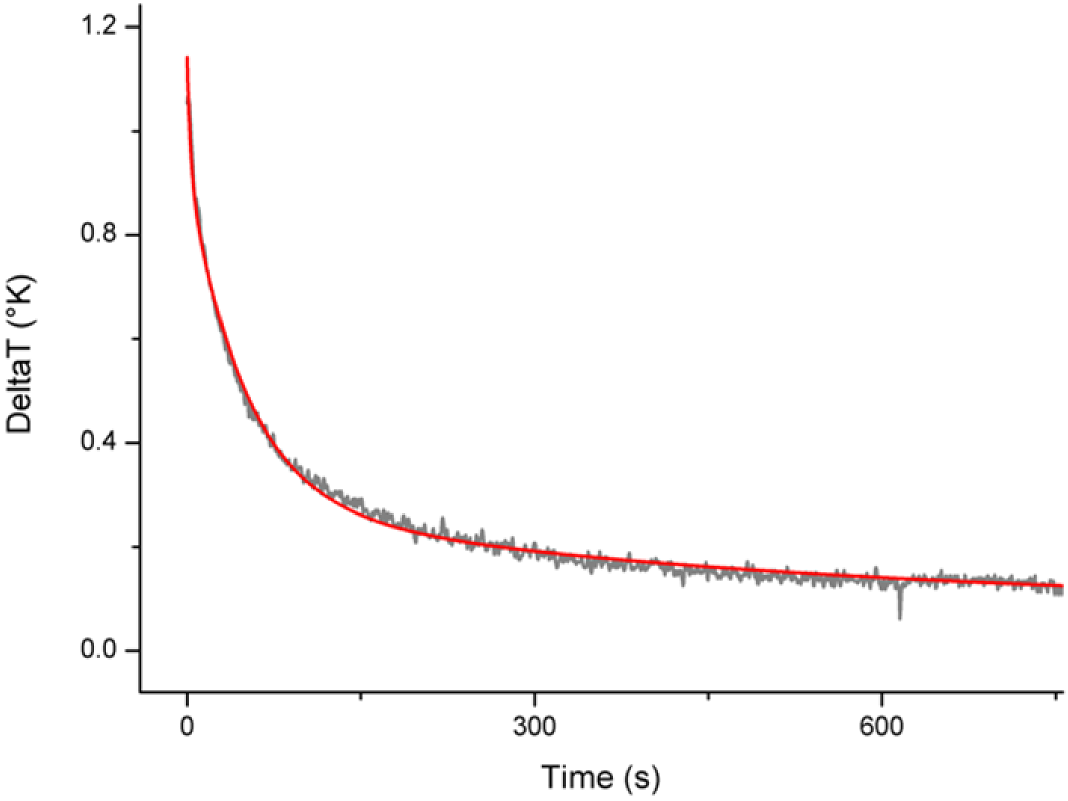


$$\rho = (3.2 \pm 0.4) \cdot 10^{-8}\ \Omega\mathrm{m}$$

$$\rho_{EFF} = (3.6 \pm 0.4) \cdot 10^{-8}\ \Omega\mathrm{m}$$

Heat transfer coefficient

$$\Delta T(t) = \Delta T(0) + A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + A_3 e^{-t/\tau_3}$$



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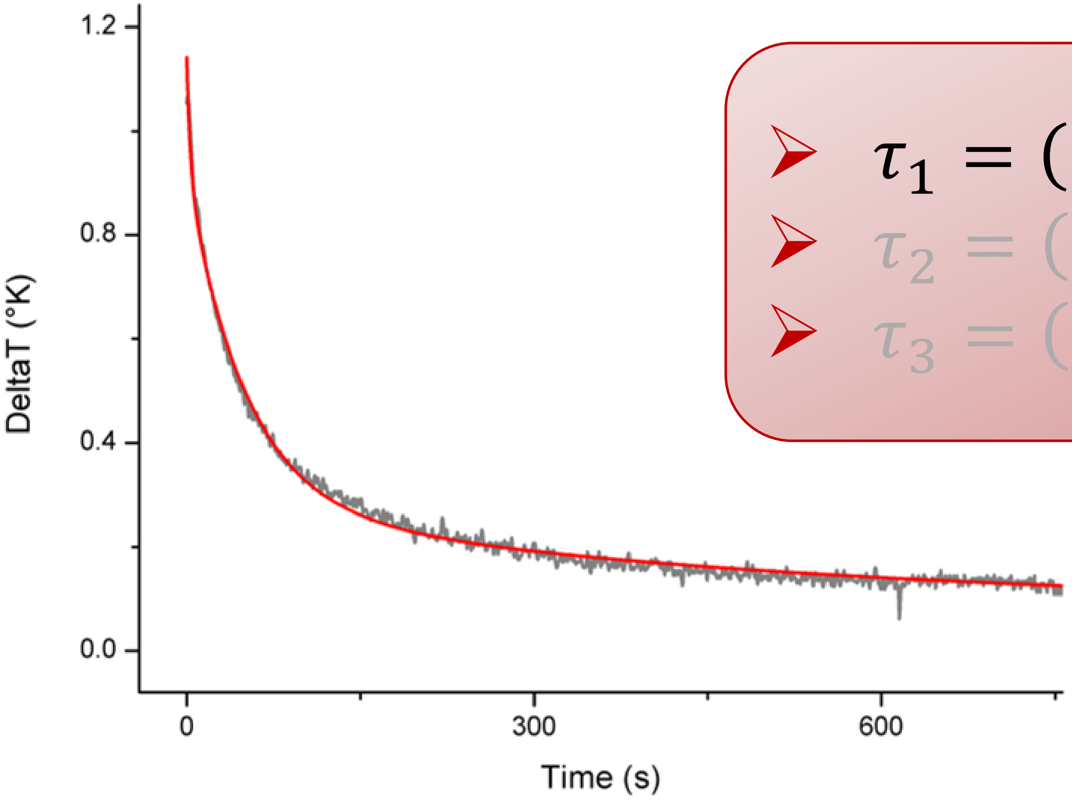

- $\tau_1 = (3.0 \pm 0.2)$ s
- $\tau_2 = (47 \pm 2)$ s
- $\tau_3 = (475 \pm 5)$ s

Heat transfer coefficient

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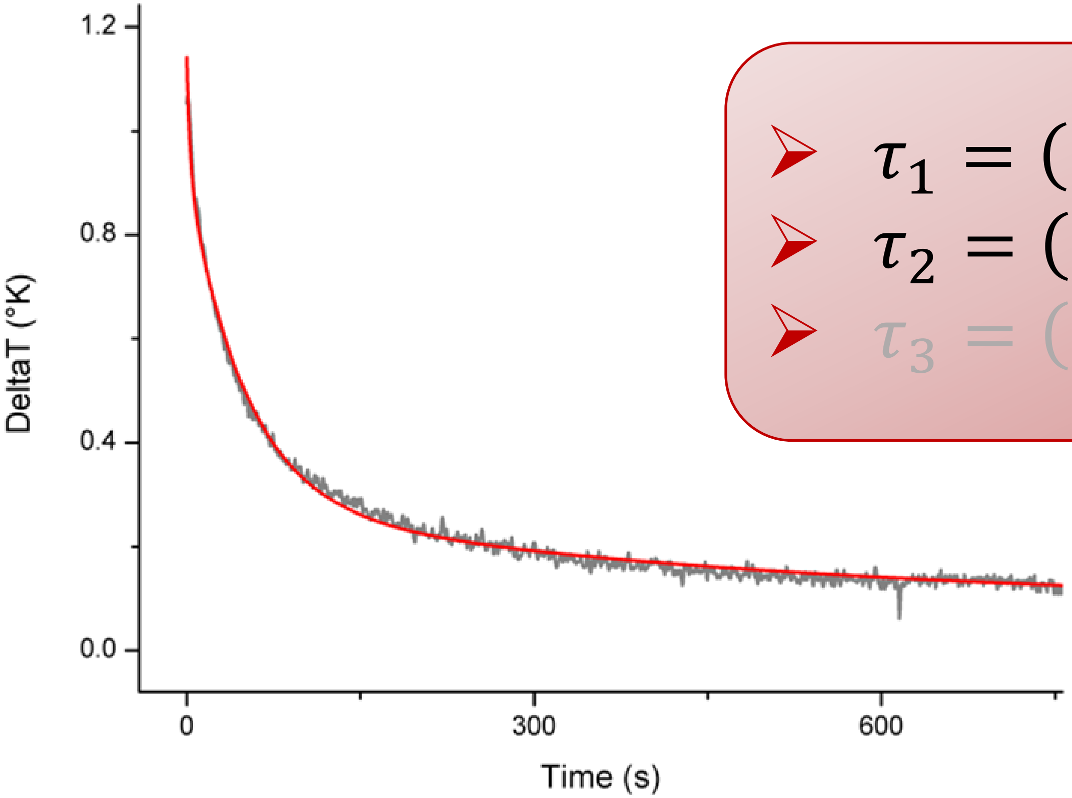
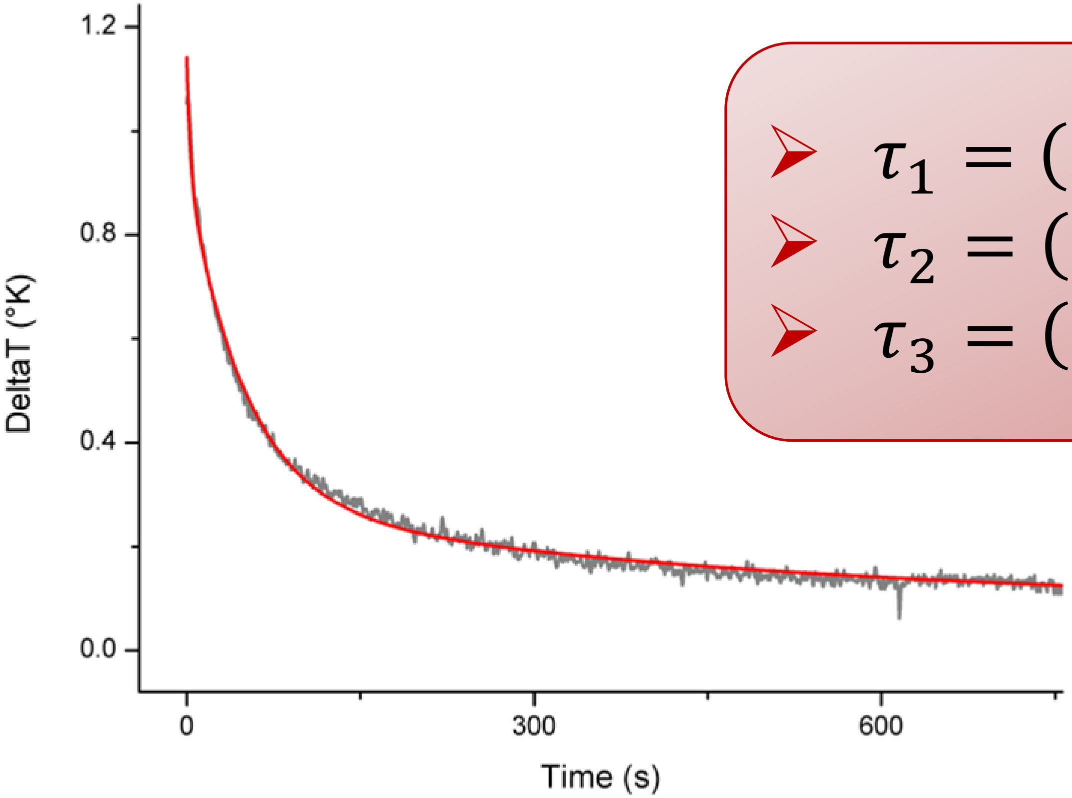


- $\tau_1 = (3.0 \pm 0.2)\ \mathrm{s}$
- $\tau_2 = (47 \pm 2)\ \mathrm{s}$
- $\tau_3 = (475 \pm 5)\ \mathrm{s}$

Heat transfer coefficient

$$\Delta T(t) = \Delta T(0) + A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + A_3 e^{-t/\tau_3}$$



- $\tau_1 = (3.0 \pm 0.2)$ s
- $\tau_2 = (47 \pm 2)$ s
- $\tau_3 = (475 \pm 5)$ s

D_2 exposure, 4-wire

SAMPLE G1

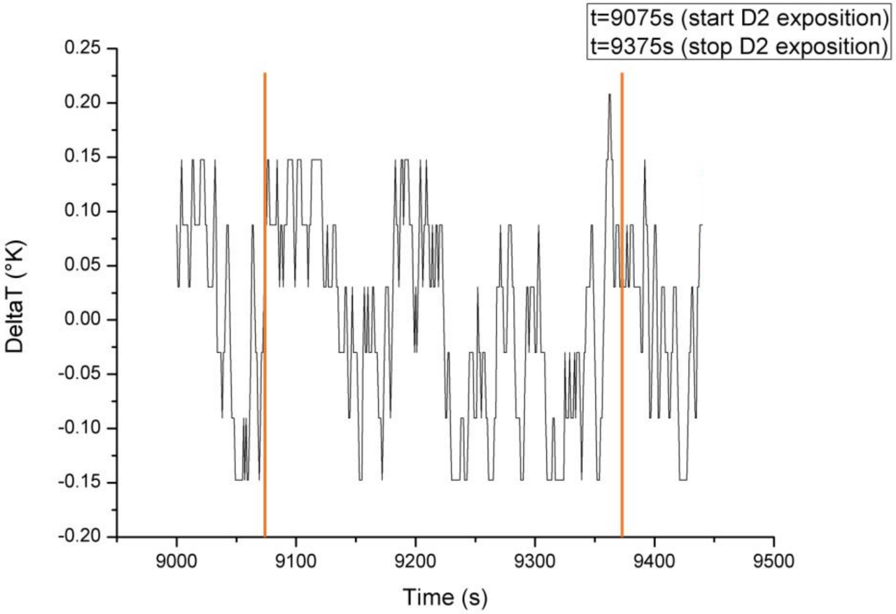
Ti deposition → $15.6\ \mathrm{ML}\ (100\%\ \mathrm{coverage})$

$P_{chamber} \sim 5 \cdot 10^{-10}\ \mathrm{mbar}$

$P_{D_2} = 1.0 \cdot 10^{-7}$ mbar for 5 minutes

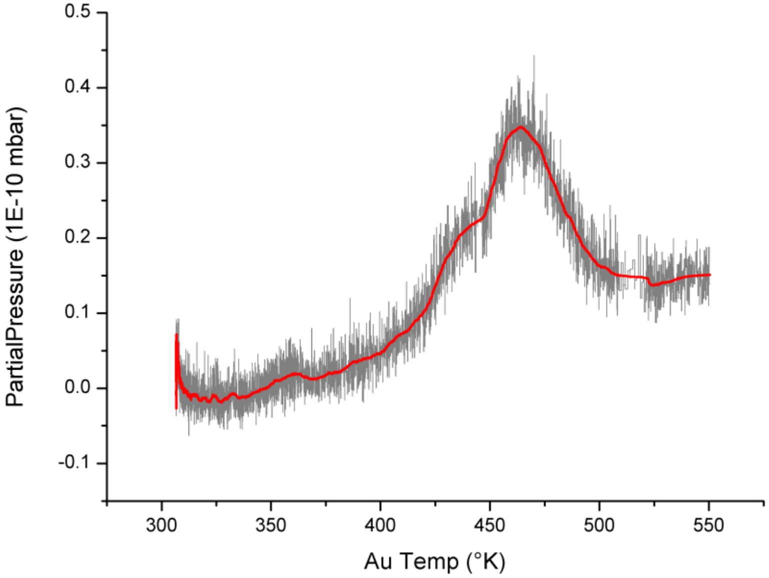
D_2 exposure, 4-wire

No ΔT detected



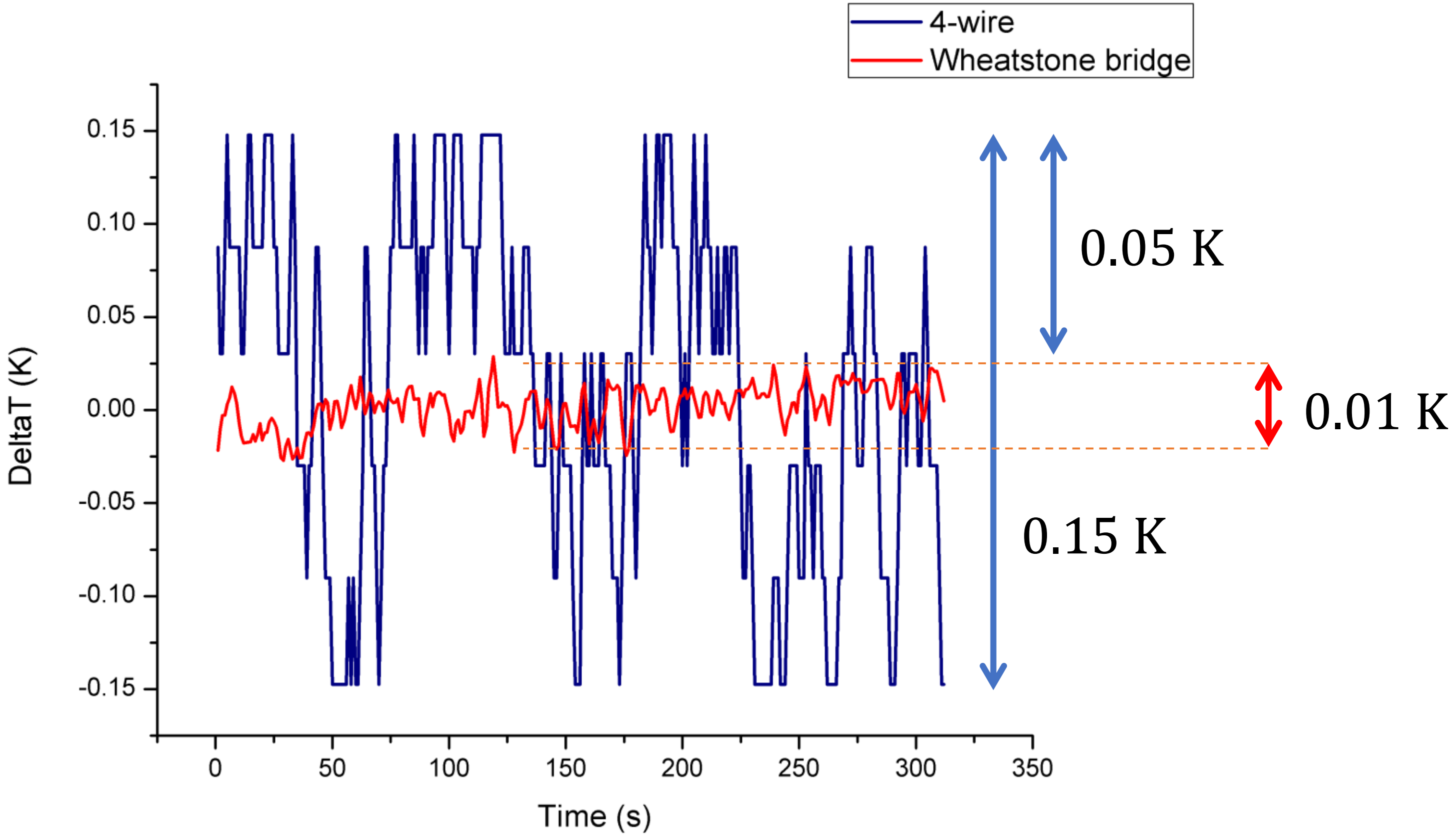
Not enough sensitivity!

TDS spectrum



Desorption Peak

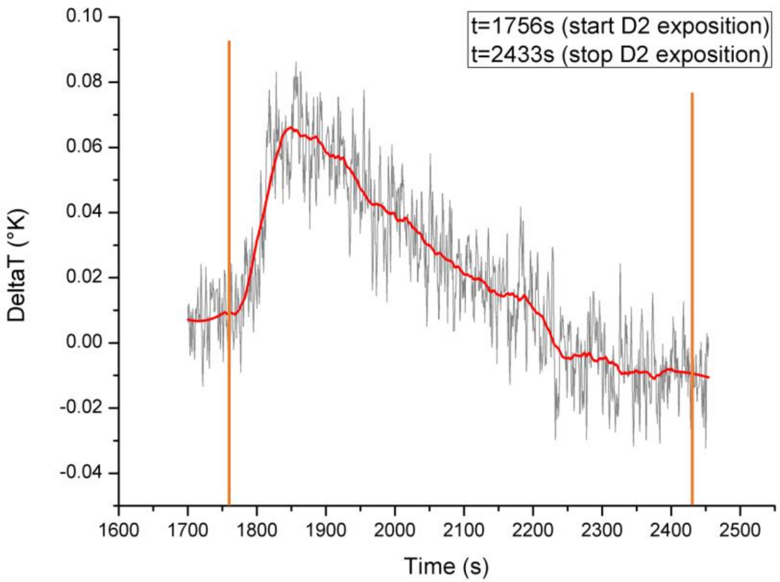
Wheatstone bridge, noise level



D_2 exposure, calorimetric analysis

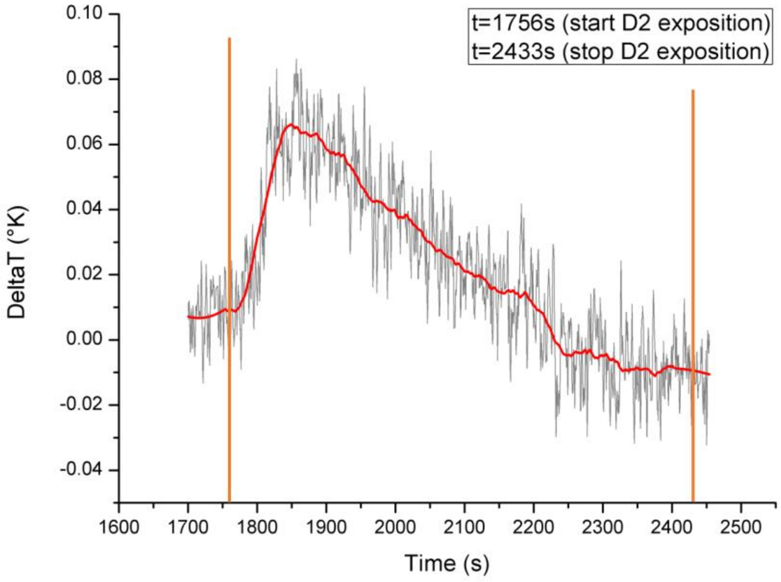
SAMPLE G3

1^{st} Ti deposition → 12.4 ML



$$\Delta T = 0.065\ \mathrm{K}$$

Calorimetric analysis



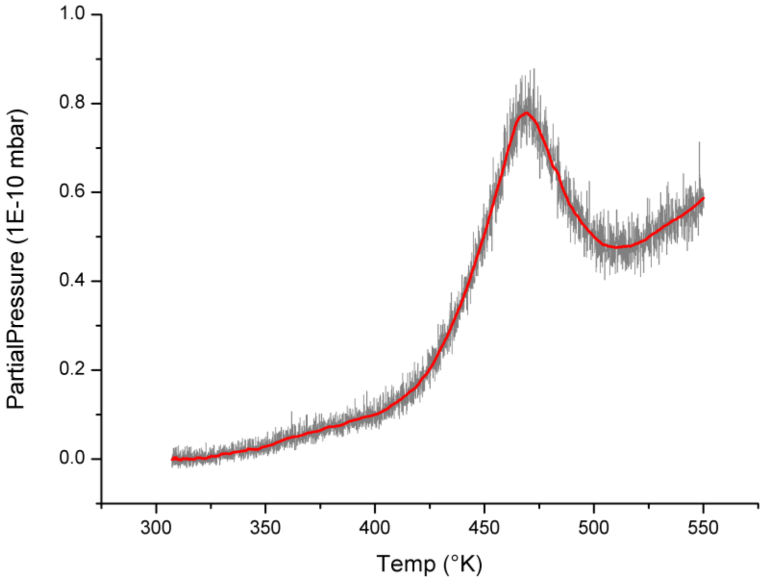
$$\Delta T = 0.065 \text{ K}$$

$$\tau = (2.94 \pm 0.63)\ s \ \rightarrow \ \lambda_{G3} = (5.1 \pm 1.1) \cdot 10^{-6} \text{ W/K}$$

$$H_r = (23.4 \pm 4.7)\ \mu\text{J}$$

TDS analysis

TDS spectrum vs Temp

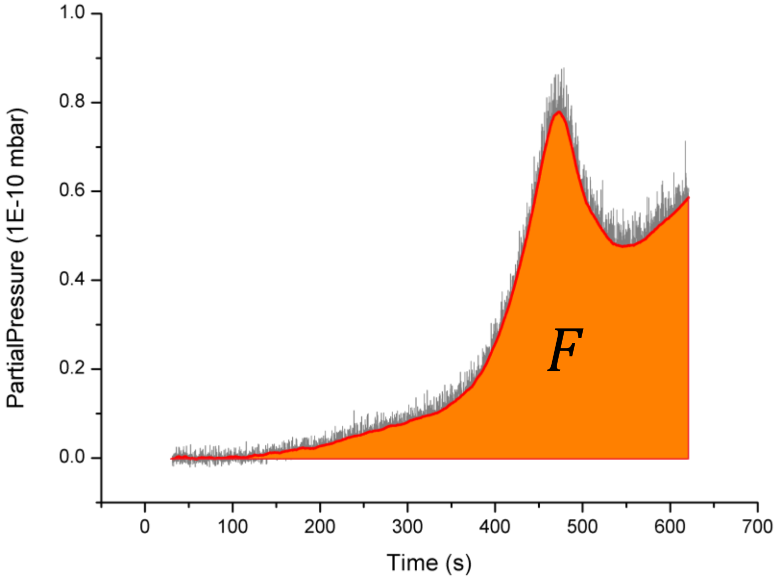


$$\frac{E_d}{k_B T_p} = A\,\tau_m \exp\left(-\frac{E_d}{k_B T_p}\right)$$

$$T_p = (495 \pm 3)\ \mathrm{K} \rightarrow E_d = (1.32 \pm 0.07)\ \mathrm{eV/molecule}$$

TDS analysis

TDS spectrum vs time



$$\boxed{p\,V = F\,S = n\,R\,T}$$

$$S \approx 300\,\mathrm{L/s}$$

$$\downarrow$$

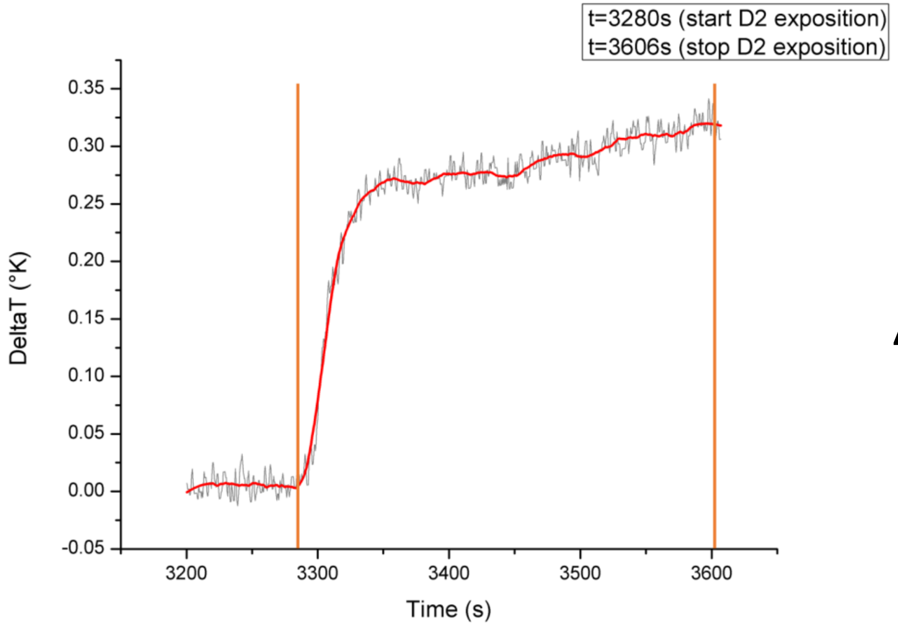
$$n(D_2) \rightarrow 1.71 \cdot 10^{-10}\ \mathrm{mol}$$

$$H_r = n\,N_A\,E_b = (23.4 \pm 4.7)\ \mu\mathrm{J}$$

D_2 exposure, calorimetric analysis

SAMPLE G3

2^{nd} Ti deposition → 16.6 ML

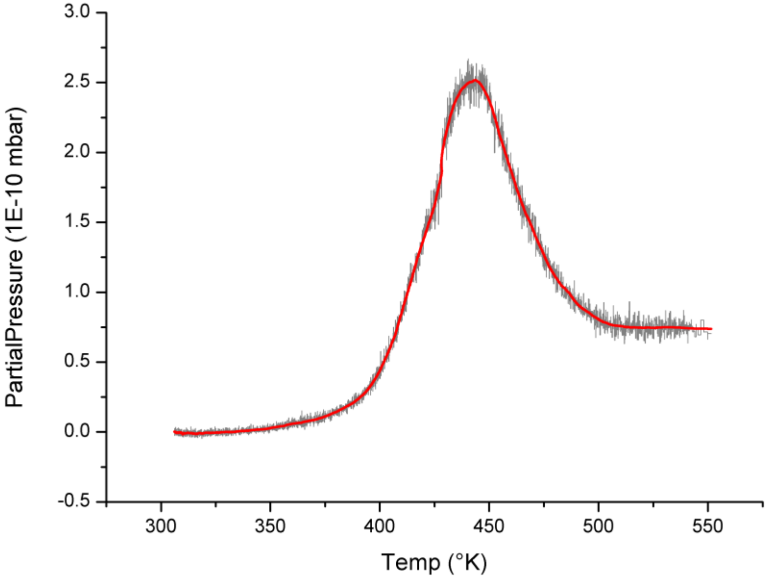


$$\Delta T = 0.25\ \mathrm{K}$$

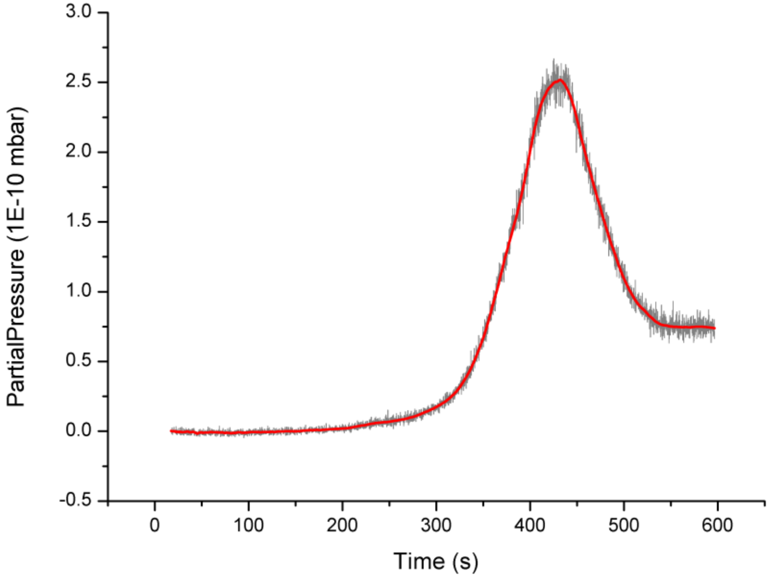
$$H_r = (58 \pm 12)\ \mu\mathrm{J}$$

TDS analysis

TDS spectrum vs Temp



TDS spectrum vs time



$$T_p = (442 \pm 3)\ \mathrm{K}$$

$$\downarrow$$

$$E_d = (1.24 \pm 0.09)\ \mathrm{eV/molecule}$$

$$n(D_2)\ \rightarrow 4.50 \cdot 10^{-10}\ \mathrm{mol}$$

$$\downarrow$$

$$H_r = (53.8 \pm 4.3)\ \mu\mathrm{J}$$

Comparison of E_d and H_r

	Ti (ML)	E_d/molecule (eV)	H_r (μJ)	
			calorimetry	TDS
$G2_{(1)}$	8.4	1.29 ± 0.02	22 ± 11	6.75 ± 0.16
$G2_{(2)}$	16.5	1.30 ± 0.06	34 ± 17	26.4 ± 1.4
$G3_{(1)}$	12.4	1.32 ± 0.07	23.4 ± 4.7	21.8 ± 1.3
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CONCLUSIONS

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○ design of an experimental setup able to directly detect the small H_r during the adsorption of D_2

$$\Delta T \sim 0.01\ \mathrm{K} \quad (\Delta R \sim 0.03\ \mathrm{m\Omega})$$

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- stable and comparable sample's properties → reliability and repeatability

- agreement between calorimetry (non destructive, direct, and scalable) and TDS

Outlook

- Different metal functionalization or atomic H

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- Different coverages (surface vs bulk)

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○ Increase the GD of the system (less Ti)

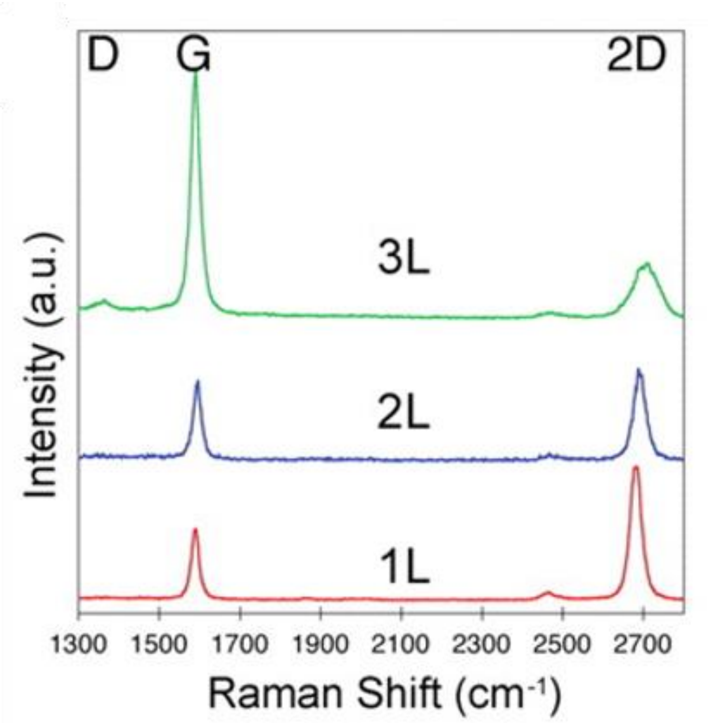
Outlook

- Different metal functionalization or atomic H
- Different coverages (surface vs bulk)
- Use the reduction of Ti-clustering (by introducing defected, amorphous or curved graphene)
- Increase the GD of the system (less Ti)
- Investigate graphene functionalized with organic molecules

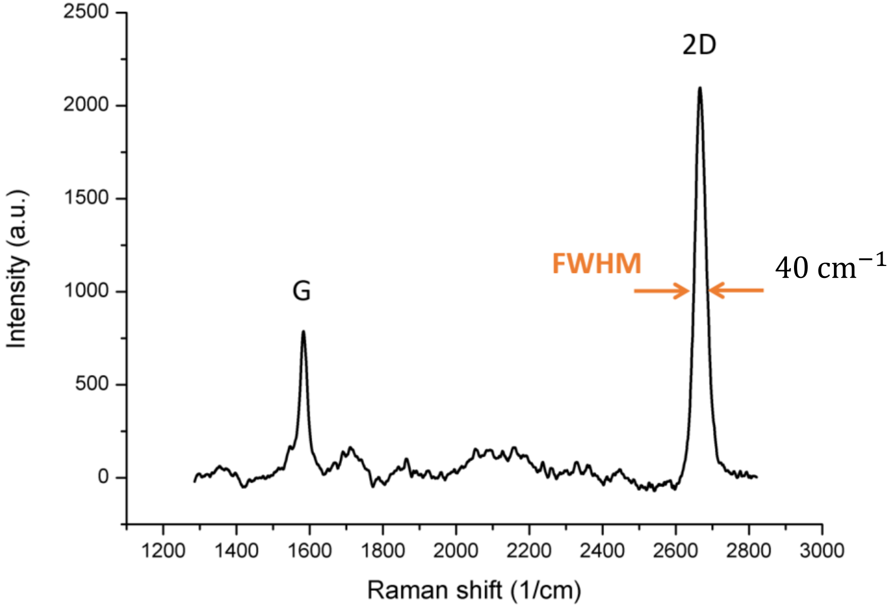
Thank you
for your attention!

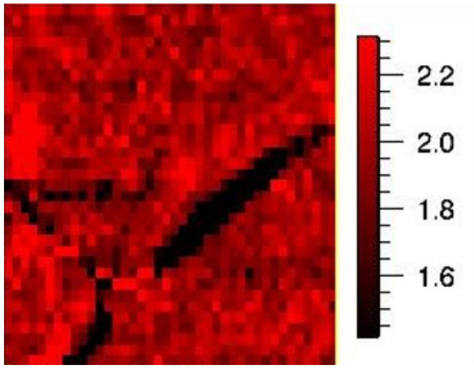
Raman spectroscopy

Raman spectrum of monolayer and multilayer graphene



Raman spectrum of the sample



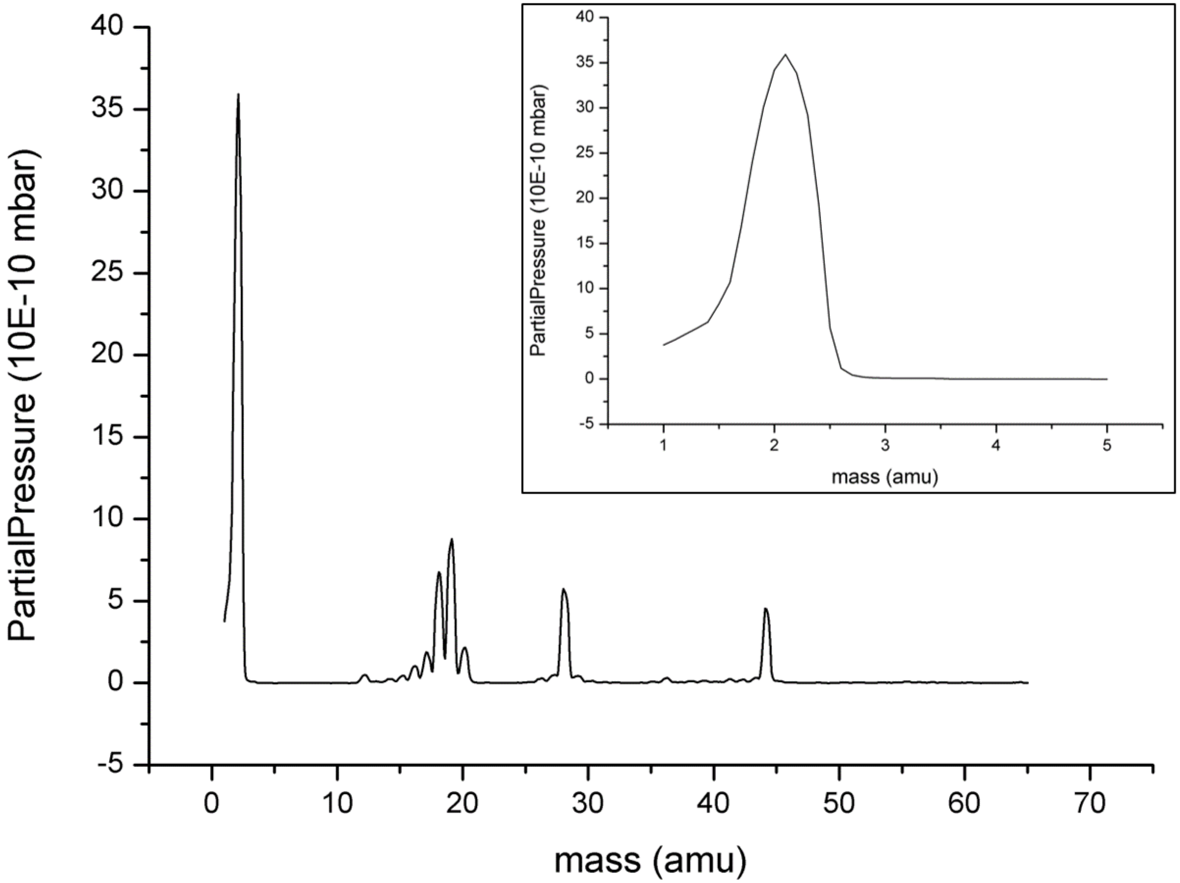


50 µm × 50 µm

Intensity ratio map:

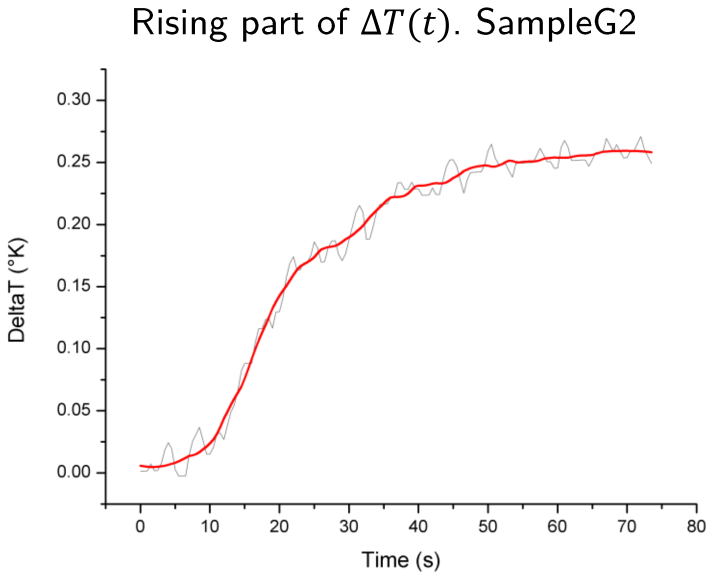
$$\frac{I_{2D}}{I_G}$$

Why D_2? → TDS

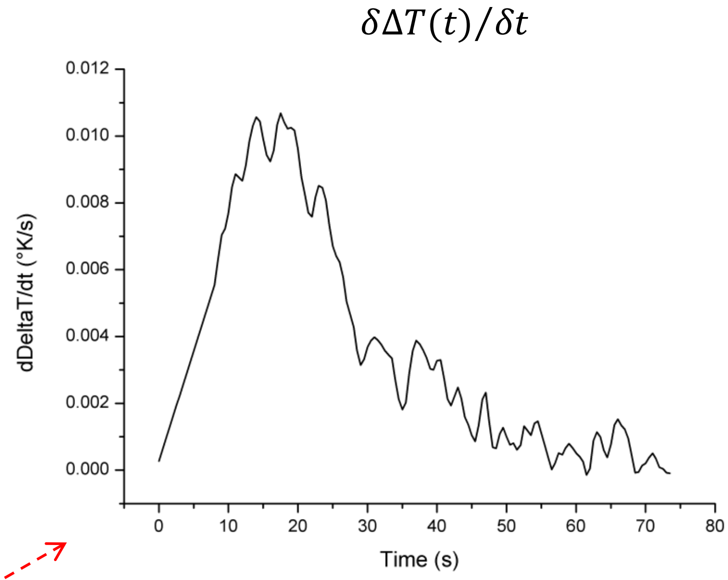


Better signal-to-noise ratio!

Calorimetric analysis

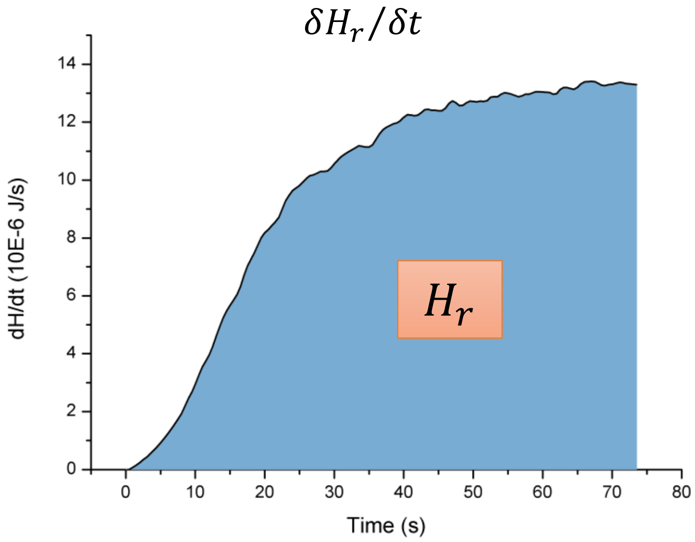


Rising part of $\Delta T(t)$. SampleG2



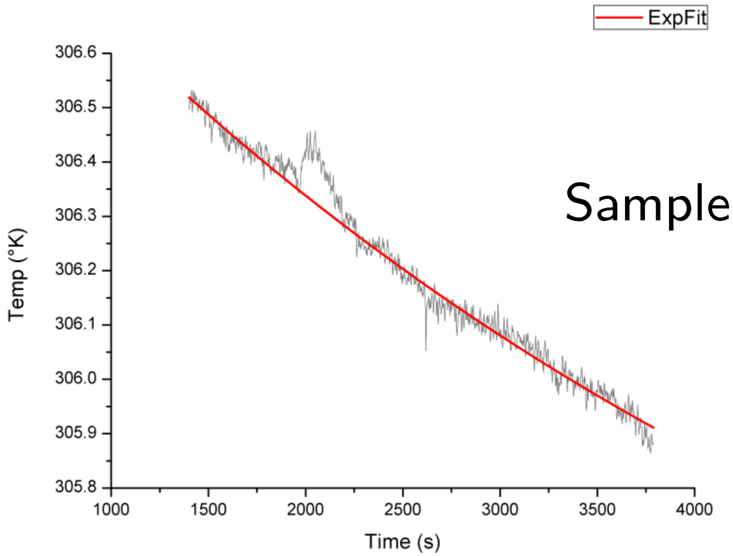
$\delta\Delta T(t)/\delta t$

$$\frac{\delta H_r(t)}{\delta t} = C\frac{\delta \Delta T(t)}{\delta t} + \lambda \Delta T(t)$$

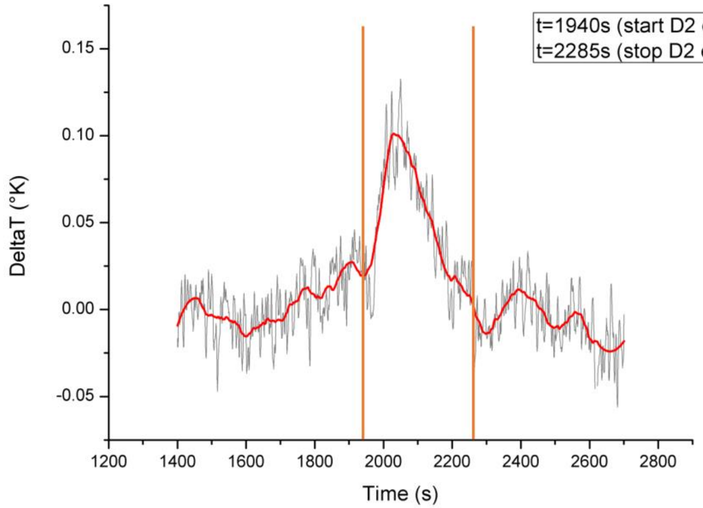


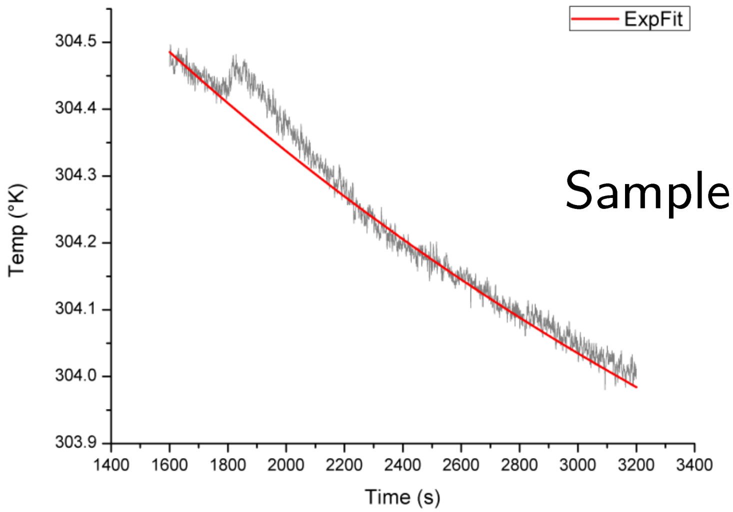
$\delta H_r/\delta t$

Subtraction of thermalization trend

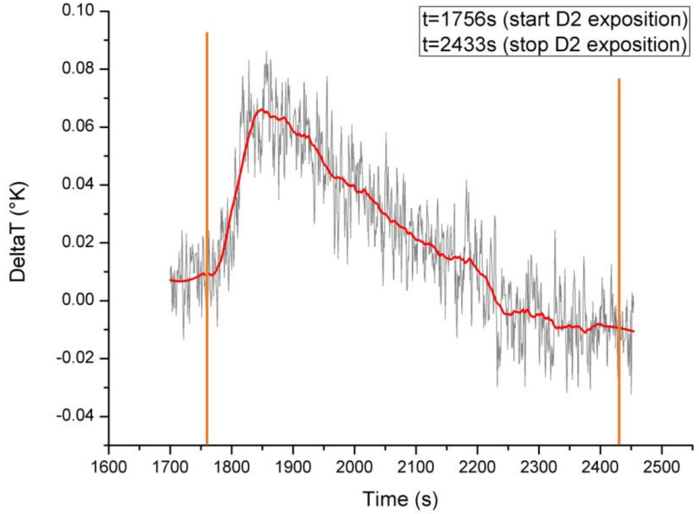


SampleG2





SampleG3



GD (using H_2)

$$M_{\mathrm{Ti}} \sim 2.37 \cdot 10^{-8}\ \mathrm{g} \quad (1\mathrm{ML})$$

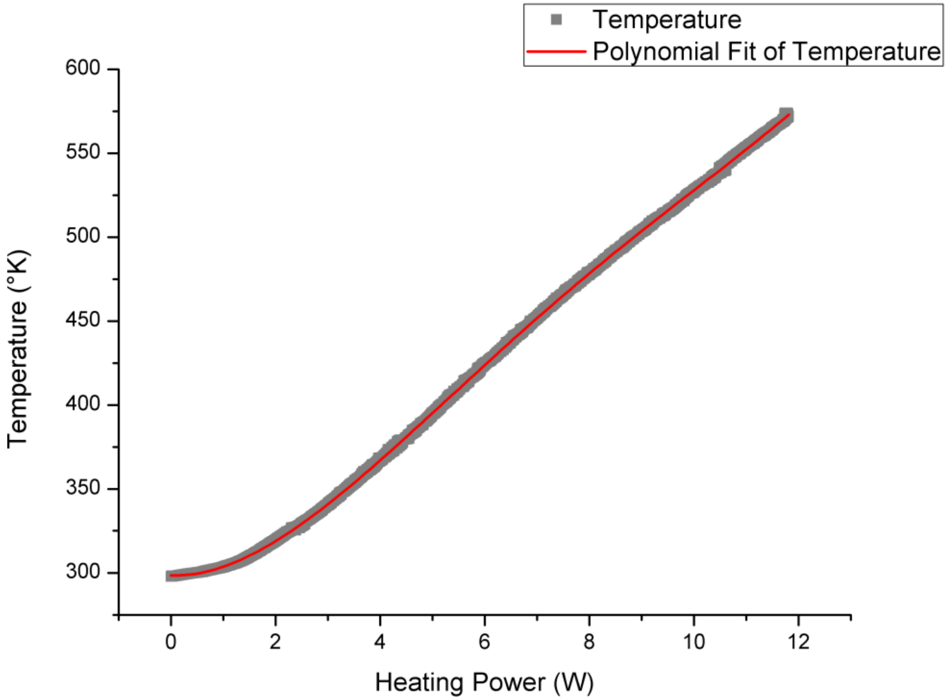
$$M_{\mathrm{Graphene}} \sim 1.71 \cdot 10^{-10}\ \mathrm{g}$$

$$M_{H_2} \sim 8.79 \cdot 10^{-10}\ \mathrm{g}$$

$$GD = \frac{M_{H_2}}{M_{\mathrm{Ti}} + M_{\mathrm{Graphene}} + M_{H_2}} \sim 2\ \mathrm{wt.\%}$$

Calibration, 2-wire setup + TC

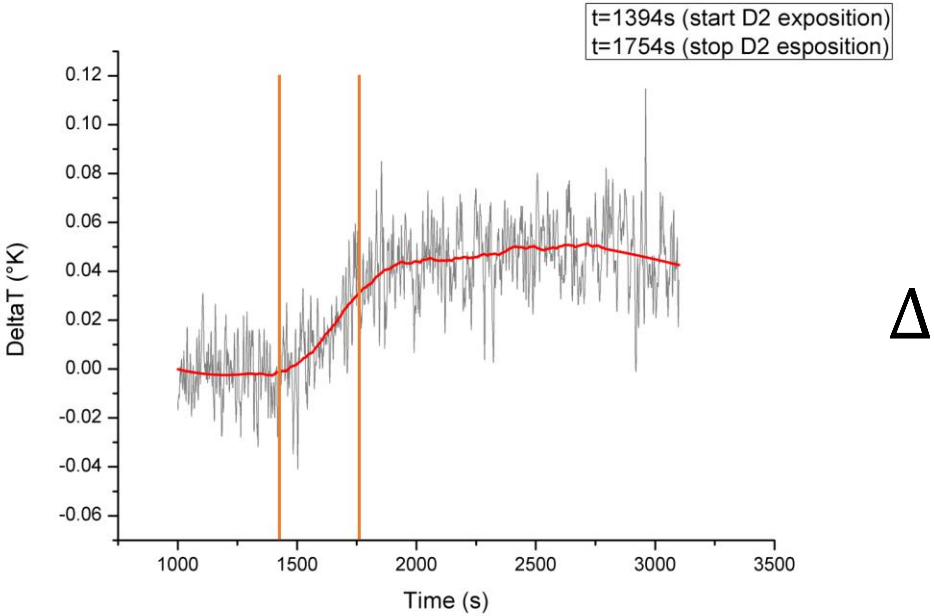
The sample is heated from RT to ~580 °K, and its temperature is calibrated via the heating power.



D_2 exposure, Wheatstone bridge

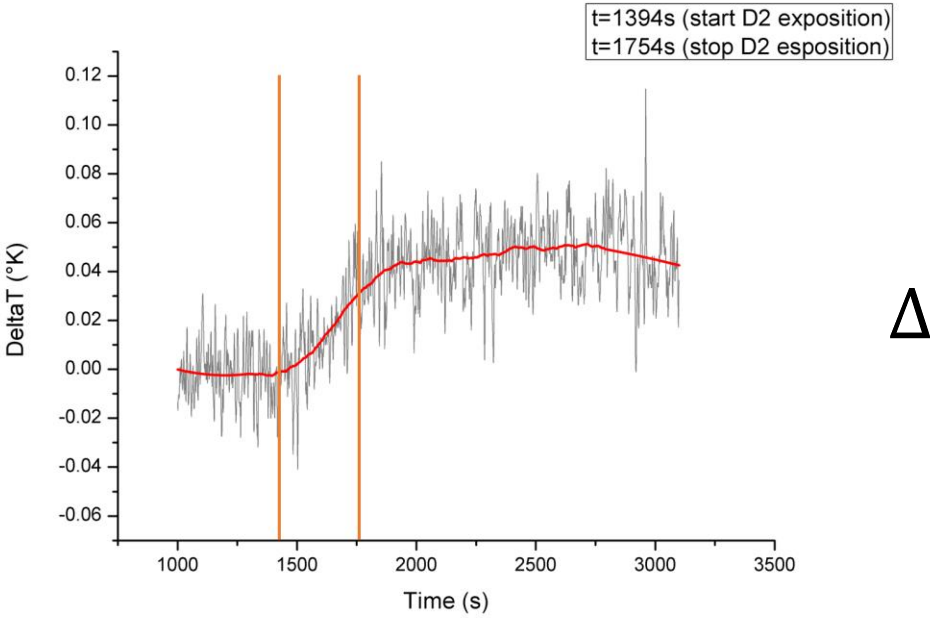
SAMPLE G2

1st Ti deposition → 8.4 ML



$$\Delta T = 0.045\ \mathrm{K}$$

Calorimetric analysis



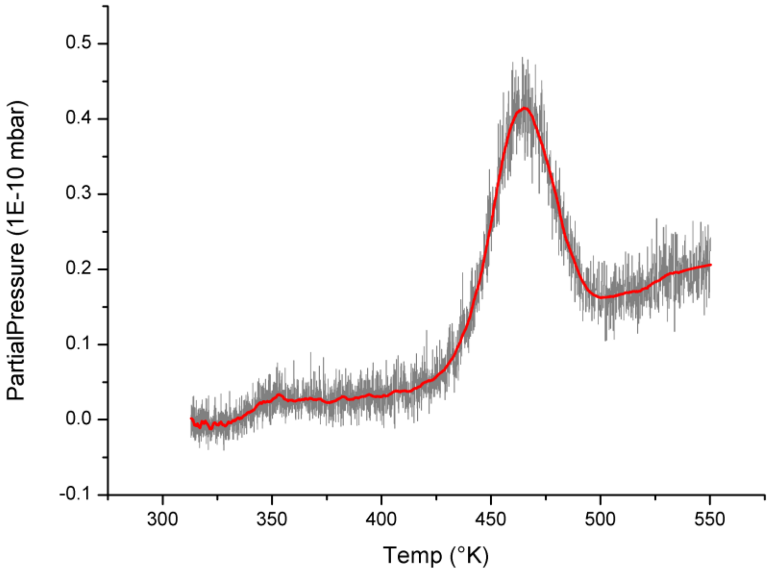
$$\Delta T = 0.045\ \mathrm{K}$$

$$\tau = (2.8 \pm 1.3)\ \mathrm{s} \ \rightarrow \ \lambda_{G2} = (5.4 \pm 2.7) \cdot 10^{-6}\ \mathrm{W/K}$$

$$H_r = (22 \pm 11)\ \mu\mathrm{J}$$

TDS analysis

TDS spectrum vs Temp

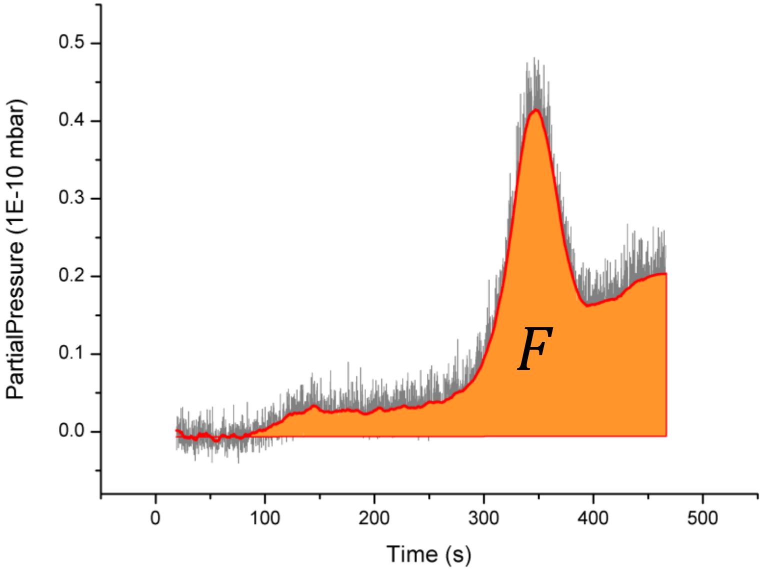


$$\boxed{\frac{E_d}{k_B T_p} = A\,\tau_m \exp\left(-\frac{E_d}{k_B T_p}\right)}$$

$$T_p = (465 \pm 3)\ \mathrm{K} \longrightarrow E_d = (1.29 \pm 0.02)\ \mathrm{eV/molecule}$$

TDS analysis

TDS spectrum vs time



$$\boxed{p\,V = F\,S = n\,R\,T}$$

$$S \approx 300\,\mathrm{L/s}$$

↓

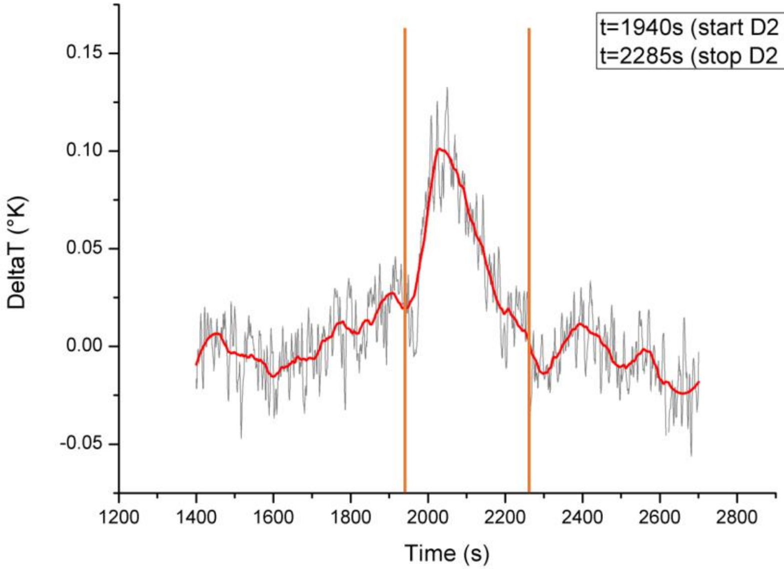
$$n(D_2) \rightarrow 5.43 \cdot 10^{-11}\,\mathrm{mol}$$

$$H_r = n\,N_A\,E_b = (6.75 \pm 0.16)\,\mu\mathrm{J}$$

D_2 exposure, calorimetric analysis

SAMPLE G2

2^{nd} Ti deposition → 16.5 ML

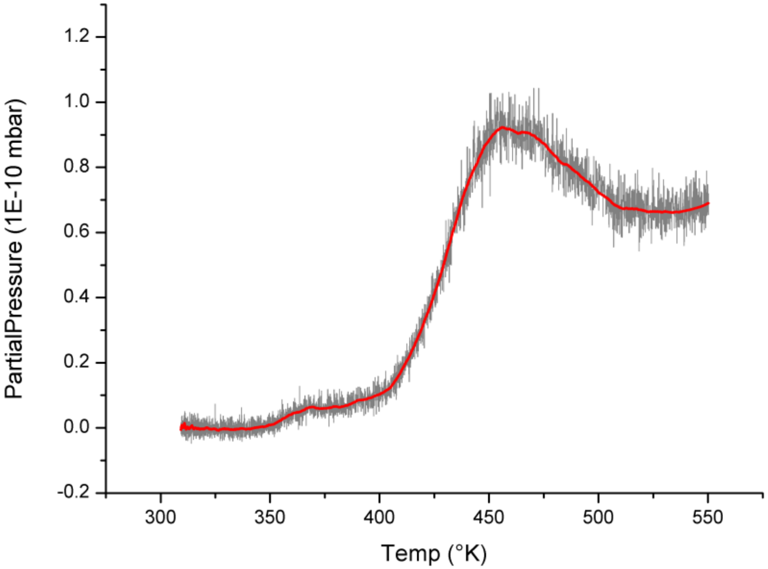


$$\Delta T = 0.10 \text{ K}$$

$$H_r = (34 \pm 17)\ \mu\text{J}$$

TDS analysis

TDS spectrum vs Temp



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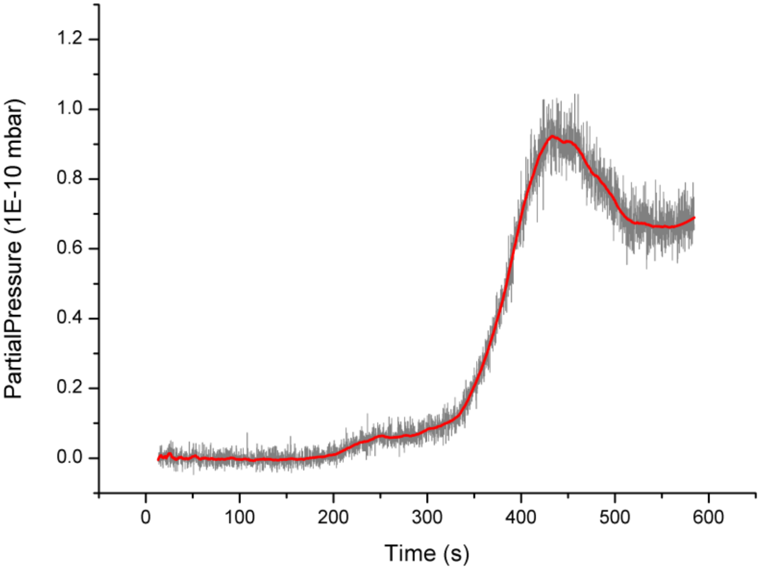

$$T_p = (459 \pm 5)\ \mathrm{K}$$

$$\downarrow$$

$$E_d = (1.30 \pm 0.06)\ \mathrm{eV/molecule}$$

$$n(D_2) \rightarrow 2.12 \cdot 10^{-10}\ \mathrm{mol}$$

$$\downarrow$$

$$H_r = (26.4 \pm 1.4)\ \mu\mathrm{J}$$