Grafen

Nobelova cena za fyziku 2010

Ludvík Smrčka

Fyzikální ústav AVČR v. v. i.

Praha

25.10.2012

Andre Geim

Flying frog

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov

"for groundbreaking experiments regarding the two-dimensional material graphene"

Nobelova cena za fyziku 2010

Andre Geim

Konstantin Novoselov

Za co byla cena udělena:

Andre Geim a Konstantin Novoselov

“za průlomové experimenty týkající se dvojrozměrného uhlíkového krystalu – grafenu”

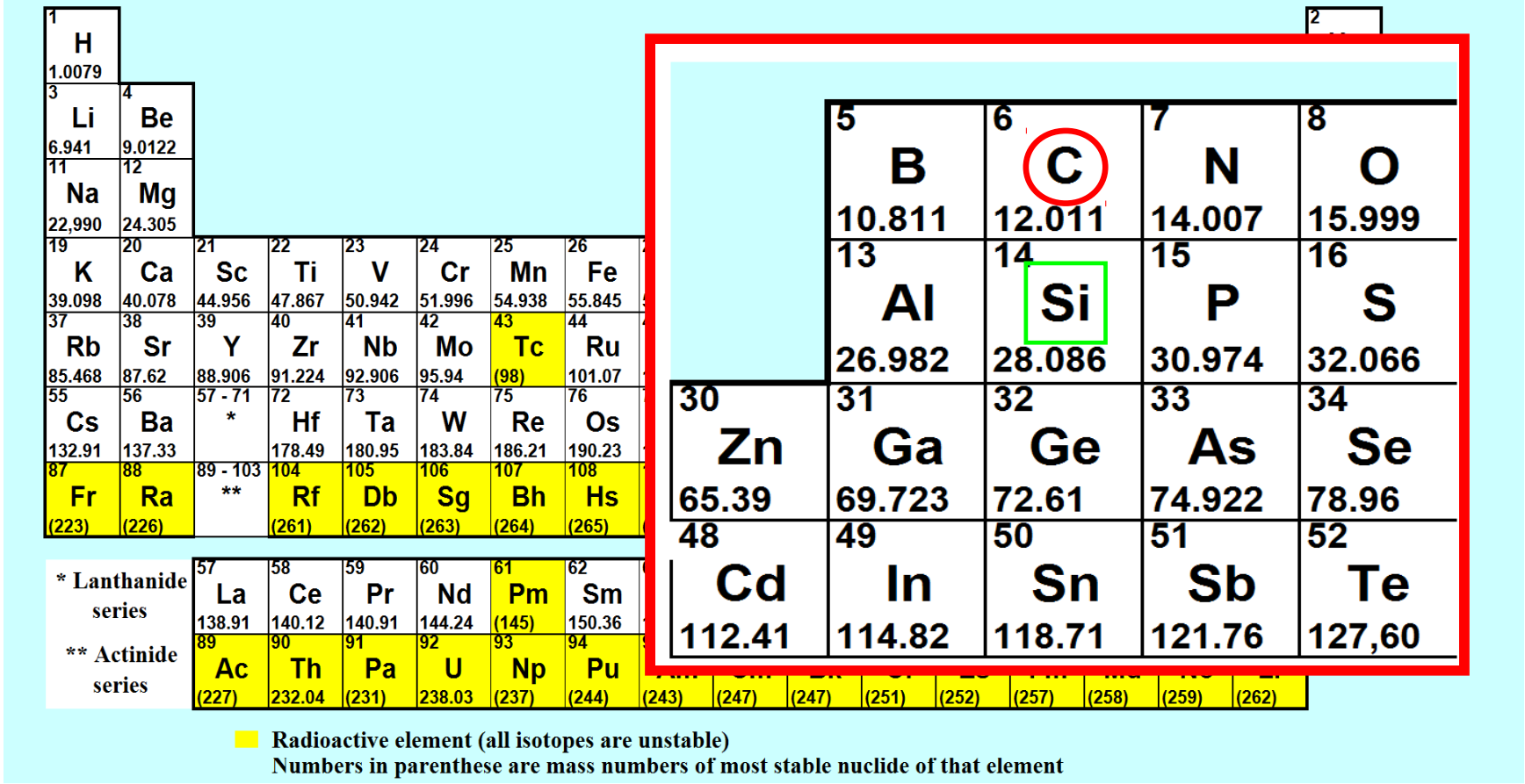
Trocha historie…..

- 1946 transistor
- 2000 Nanotechnologická iniciativa (Bill Clinton)
- Jak nahradit křemík?

Motivace…

- Najít alternativu k současným křemíkovým MOSFETům a GaAs/AlGaAs HEMTům
- Aby nebylo moc volných elektronů je třeba **tenká vrstva** …
- Neměla by být kovová…
- Nejvhodnejším kandidátem je **grafit**

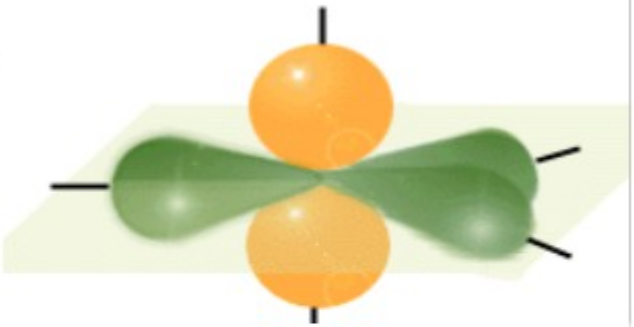
Polovodiče (Si, Ge, $A^{III}B^{V}$, A^{II} B^{VI})



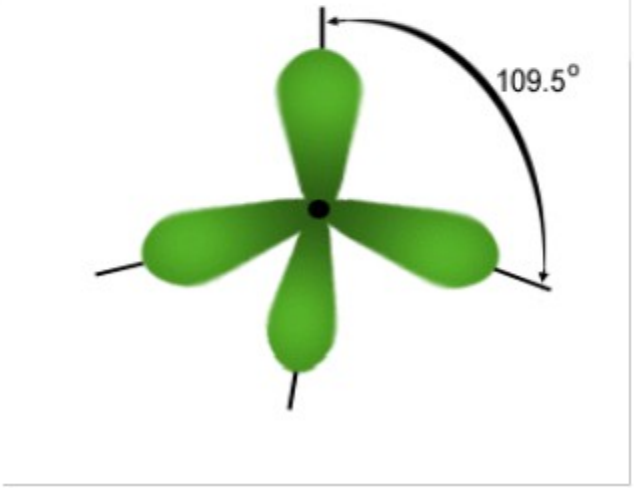
Čtyři valenční elektrony v buňce

Orbitály atomu uhlíku

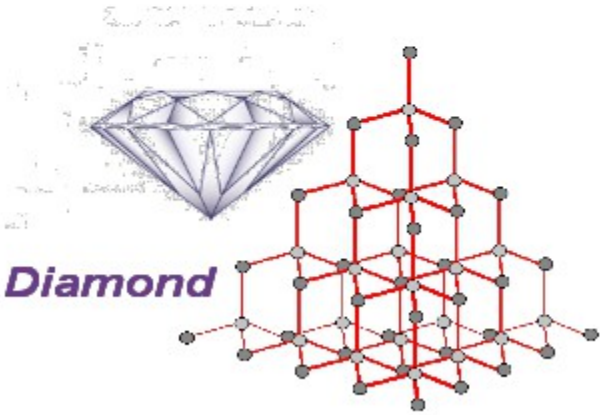
sp^2



sp^3

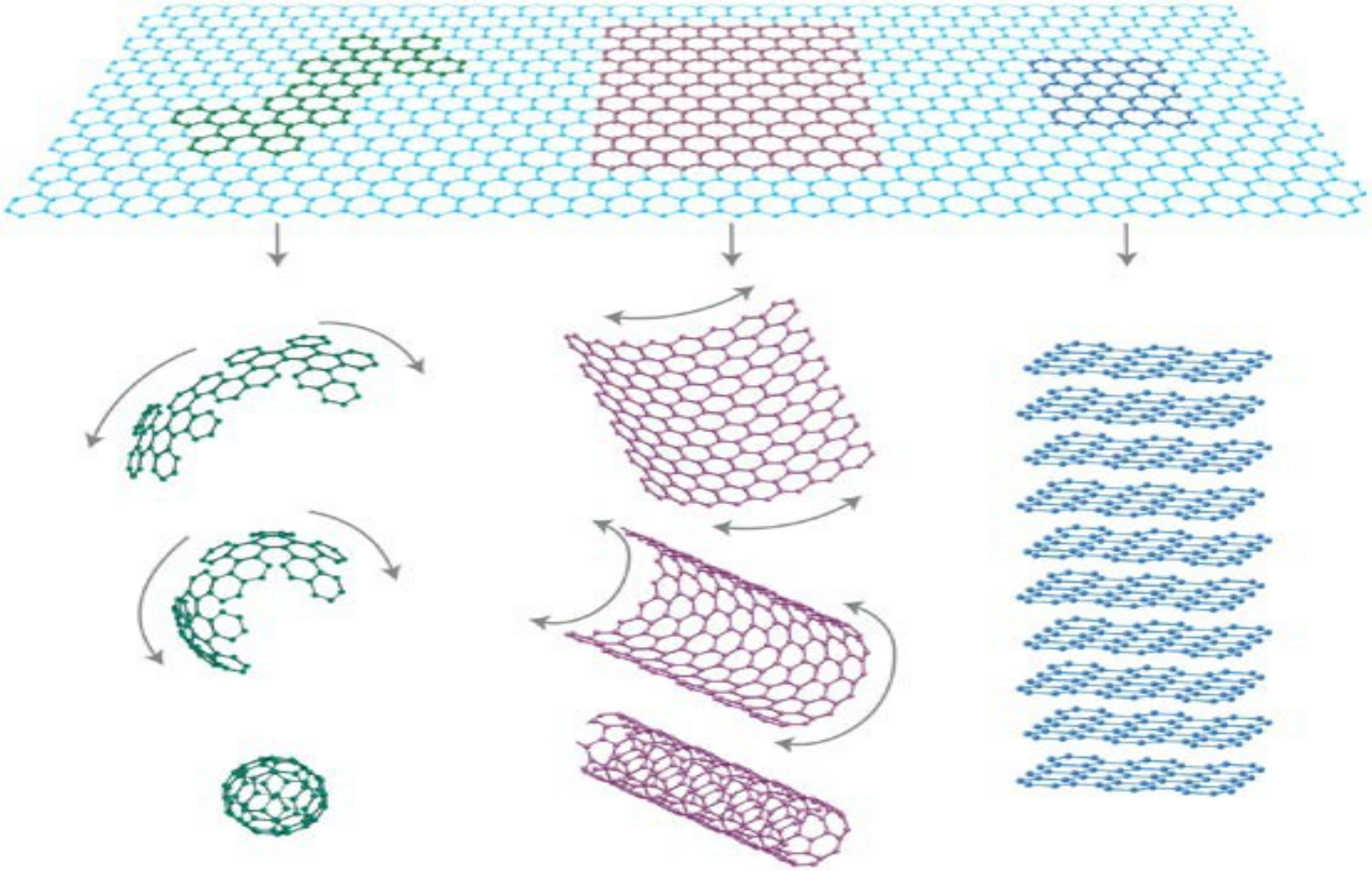


Graphite



Grafen – matka všech struktur

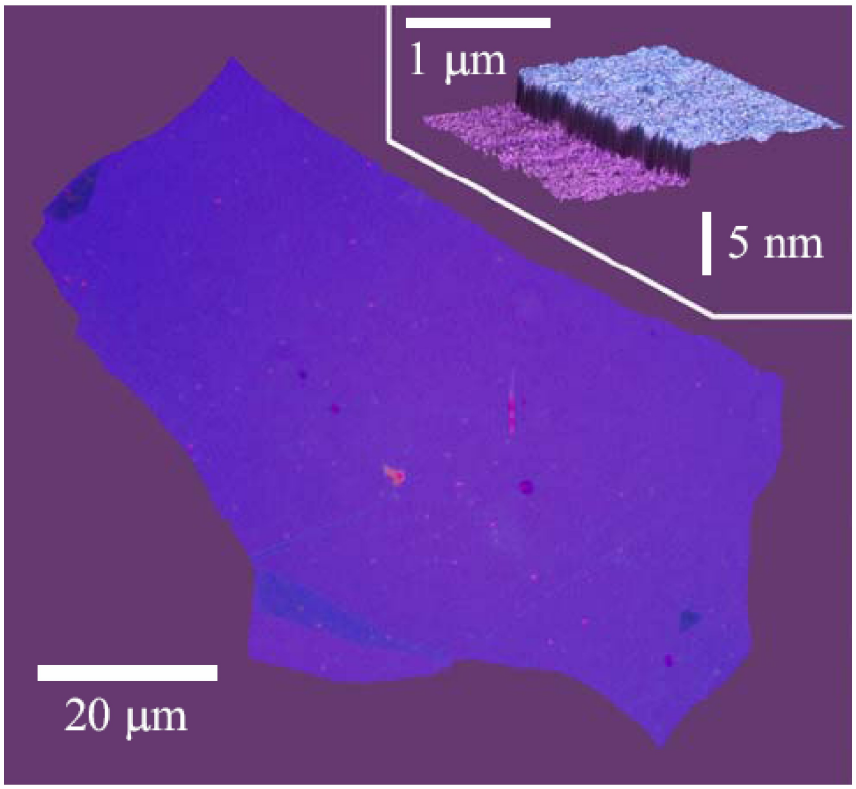
jak připravit?



Příprava grafitových vrstev exfoliací

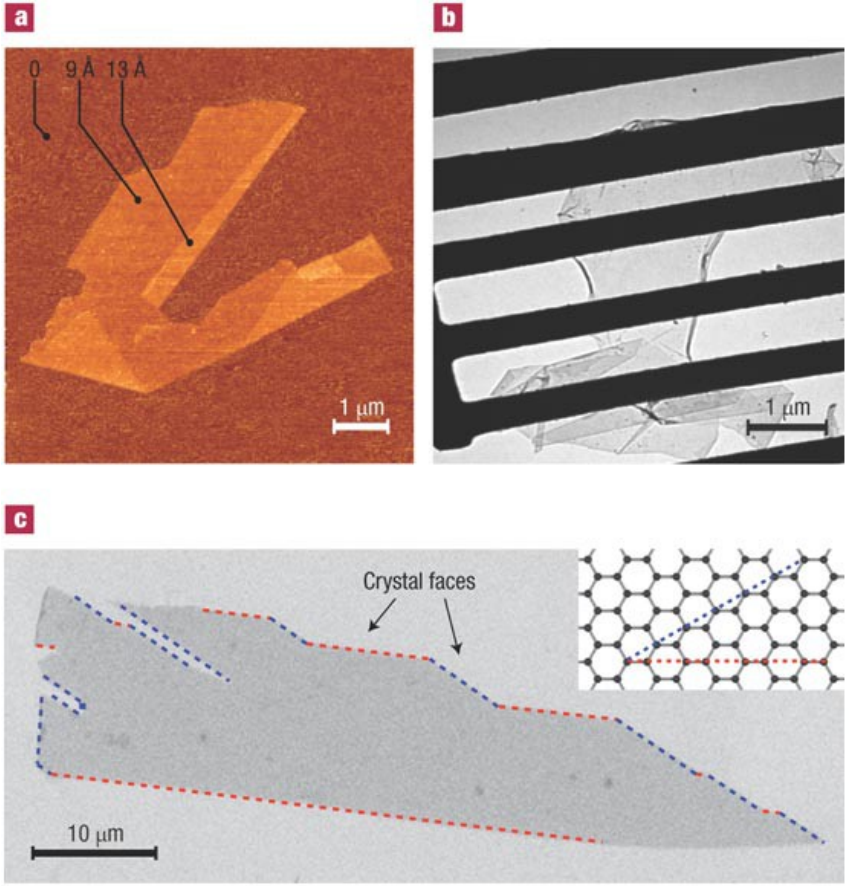
- Exfoliace – sejmutí vrstvy lepicí páskou
- Deposice vrstev na 300 nm SiO na povrchu křemíku (100)
- Identifikace vloček optickým a AFM mikroskopem

Několik vrstev grafenu



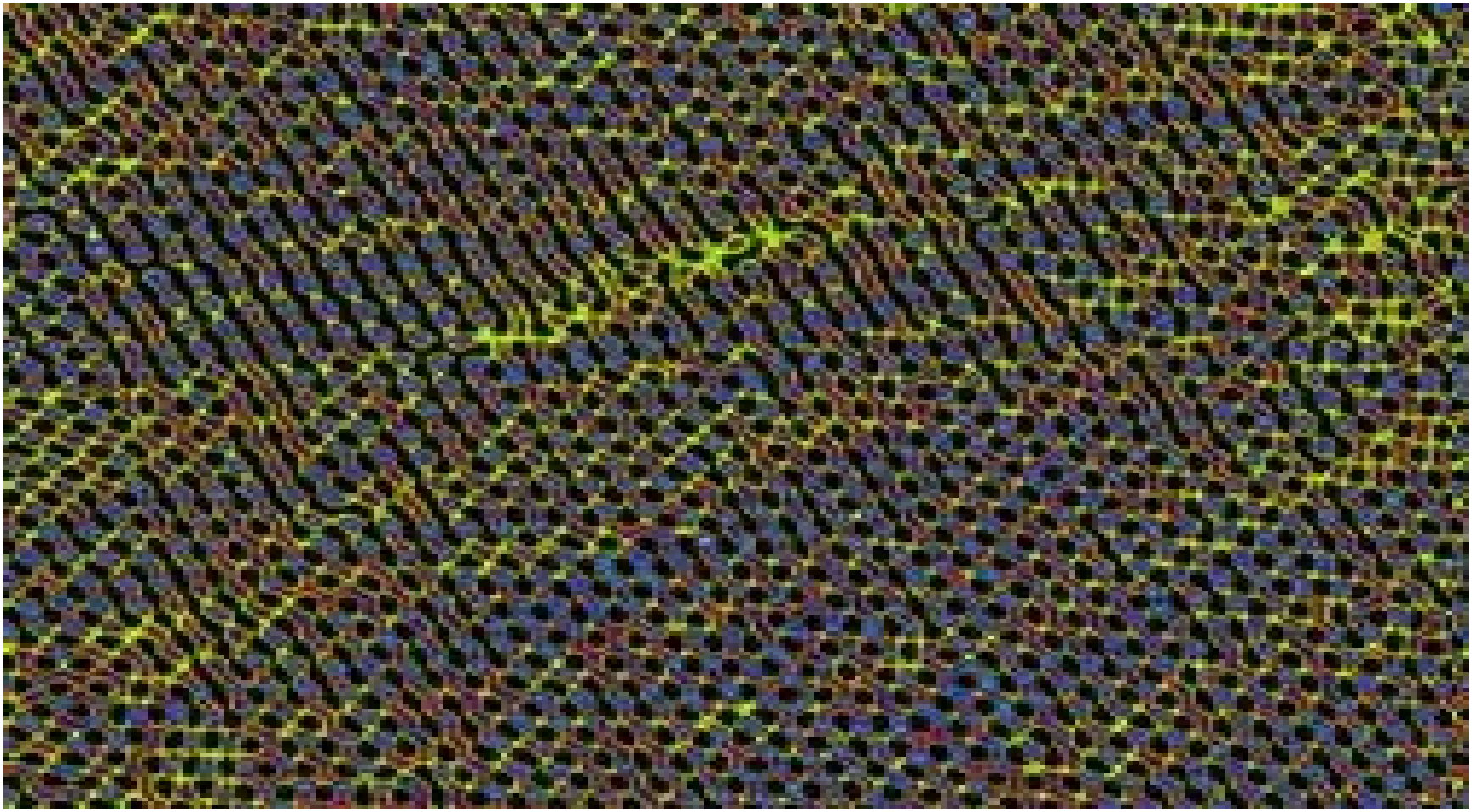
- Obrázek grafitového filmu z optického mikroskopu
- Vložen je obrázek z AFM mikroskopu
- Vzorek připravený izolepou

Jedna grafenová vrstva

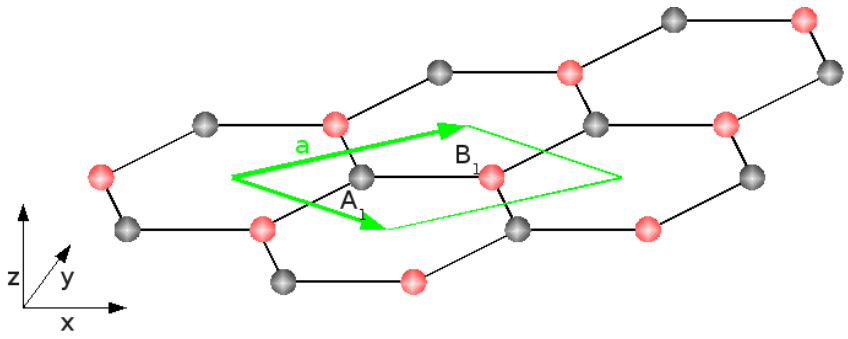


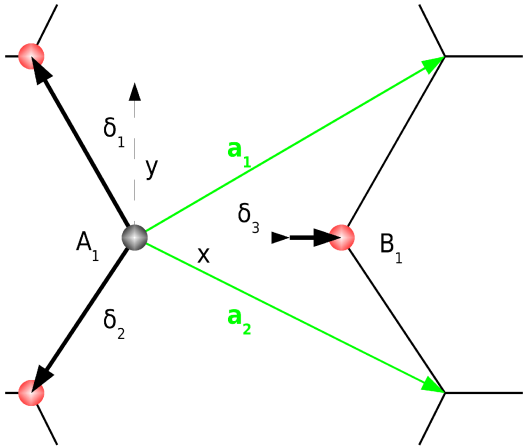
- „Psaní tužkou“ (Micromechanical cleavage)
- identifikace optickým mikroskopem
- potvrzeno AFM

Grafen skanujícím transmisním mikroskopem



Graphene – krystalová struktura





- graphite – Bernal stacking of weakly coupled single sheets
  ----graphenes----
- **two** atoms in a cell of a hexagonal Bravais lattice
- nearest neighbors tight binding electronic bands

Elektronová struktura grafenu

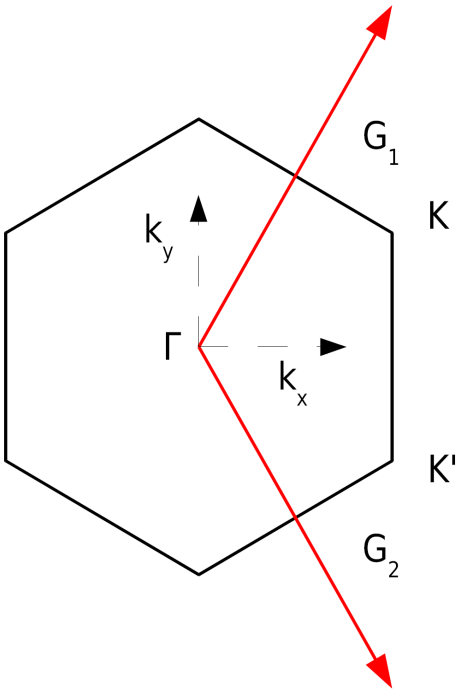
$$\Psi = a\Phi_{A1} + b\Phi_{B1}$$

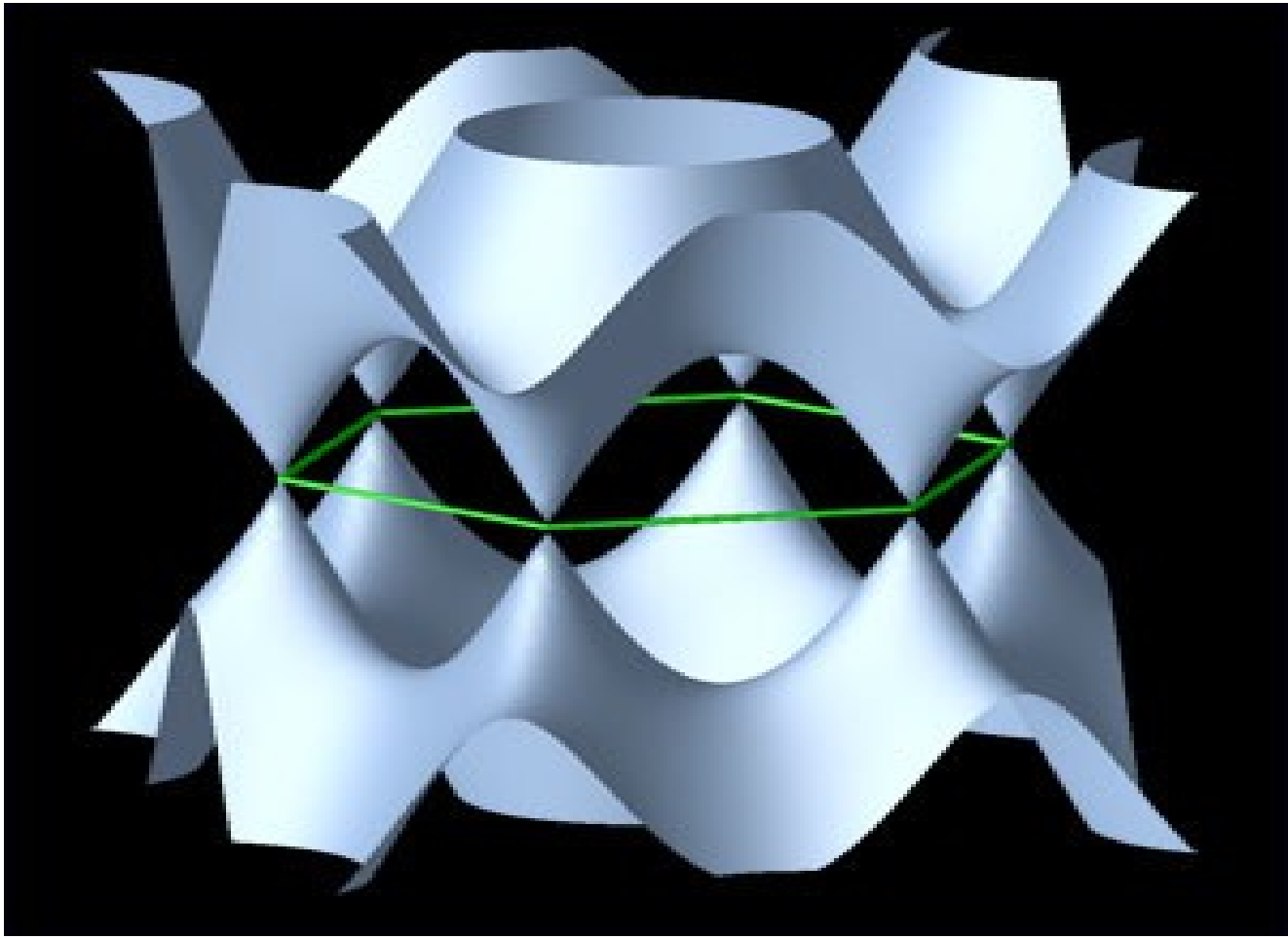
$$\Phi_{A1} = \sum_{A1} \exp\left(i\vec{k}\,\vec{R}_{A1}\right)\chi\left(\vec{r}-\vec{R}_{A1}\right) \quad \Phi_{B1} = \sum_{B1} \exp\left(i\vec{k}\,\vec{R}_{B1}\right)\chi\left(\vec{r}-\vec{R}_{B1}\right)$$

$$\begin{vmatrix} H_{A1A1}-E & H_{A1B1} \\ H_{B1A1} & H_{B1B1}-E \end{vmatrix} = 0$$

$$E_{\pm}\left(k_{x,}k_{y}\right) = \pm\sqrt{1+4\cos^{2}\left(\frac{k_{y}a}{2}\right)+4\cos\left(\frac{k_{x}\sqrt{3}a}{2}\right)\cos\left(\frac{k_{y}a}{2}\right)}$$

Elektronová struktura grafenu





Dirac massless fermions

- Power series expansion around K and K', conical low-energy spectrum, Dirac point

$$E\left(\vec{k}\right) = \pm \hbar v_F k$$

$$E^2 = \cancel{m_0^2} + c^2 p^2$$

massless

Schrödinger and Dirac fermions

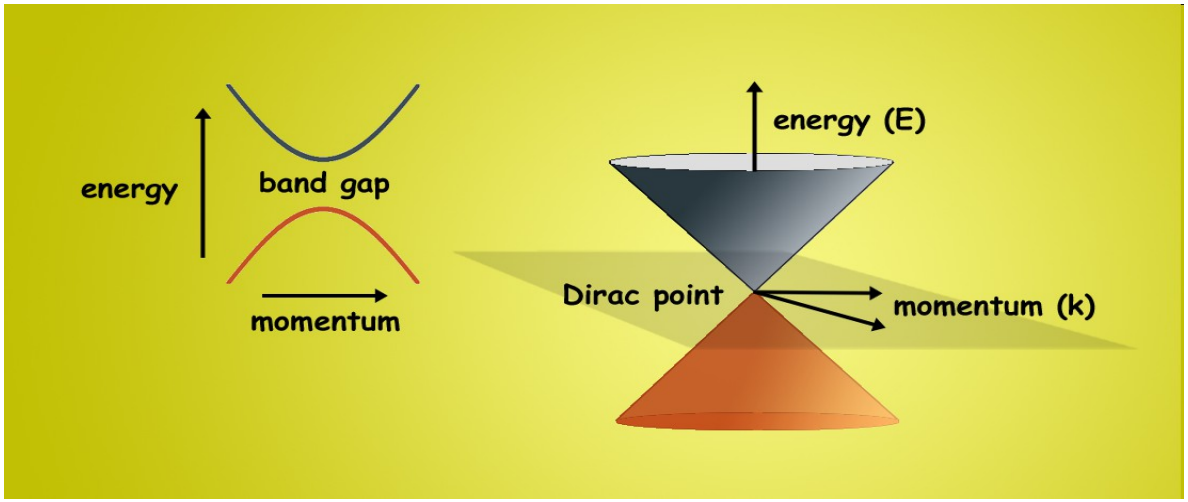
B=0

$$E^S(\vec{k}) = \frac{\hbar^2 k^2}{2\tilde{m}}$$

$$\frac{1}{\tilde{m}} = \frac{1}{\hbar^2}\frac{\partial^2 E(\vec{k})}{\partial k^2}$$

$$E^D(\vec{k}) = \pm \hbar v_F k$$

$$\vec{v} = \frac{1}{\hbar}\nabla_{\vec{k}} E(\vec{k})$$



Transportní vlastnosti v magnetickém poli a kvantový Hallův jev

Klaus von Klitzing

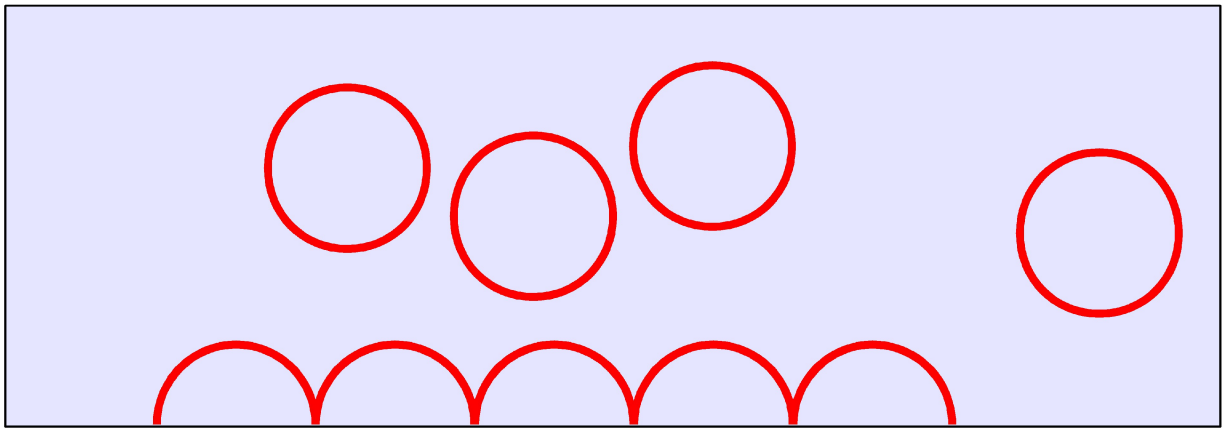
- 1985

Horst Stormer

- 1998

2DEG v magnetickém poli

Lorentzova rovnice cyklotronový pohyb a hranové orbity



Schrödinger and Dirac fermions

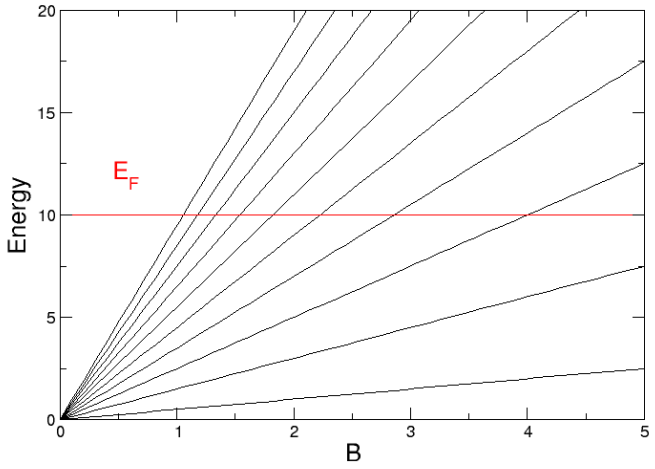
B≠0 Landau levels

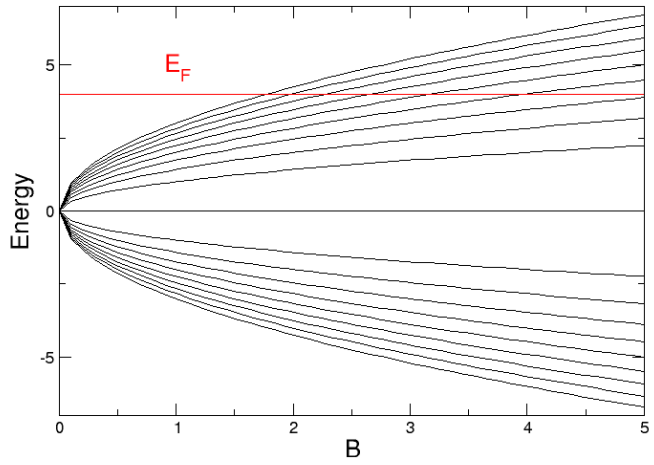
$$E_n^S = \hbar\omega_c\left(n+\frac{1}{2}\right)$$

$$\omega_c = |e|B/m$$

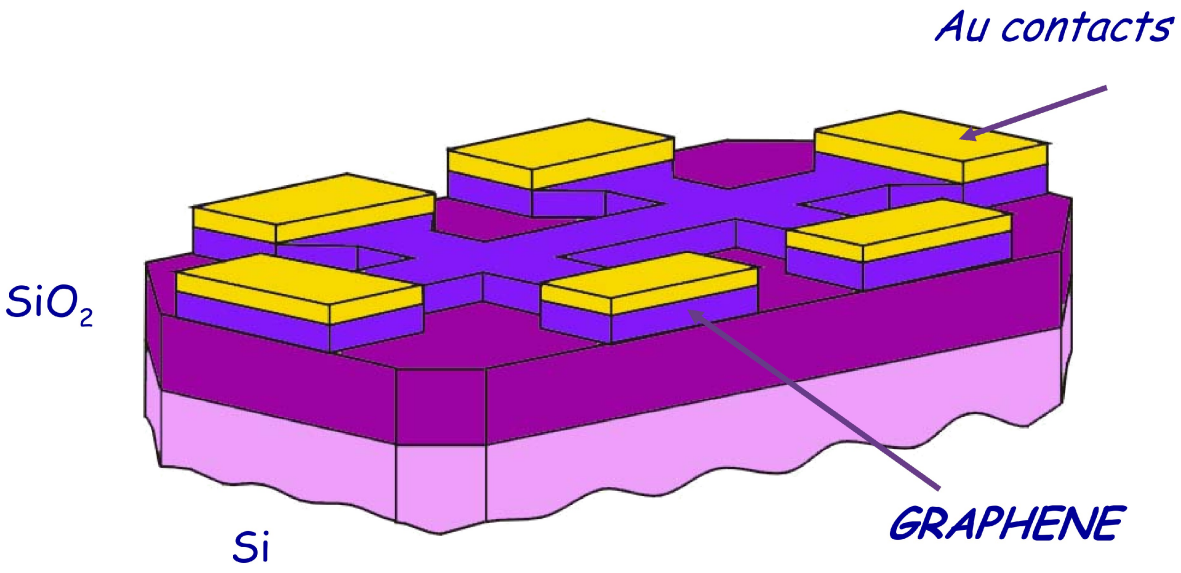
$$E_n^D = \pm\sqrt{2\hbar|e|v_F^2 Bn}$$

$$n = 0,1,2,\ldots$$

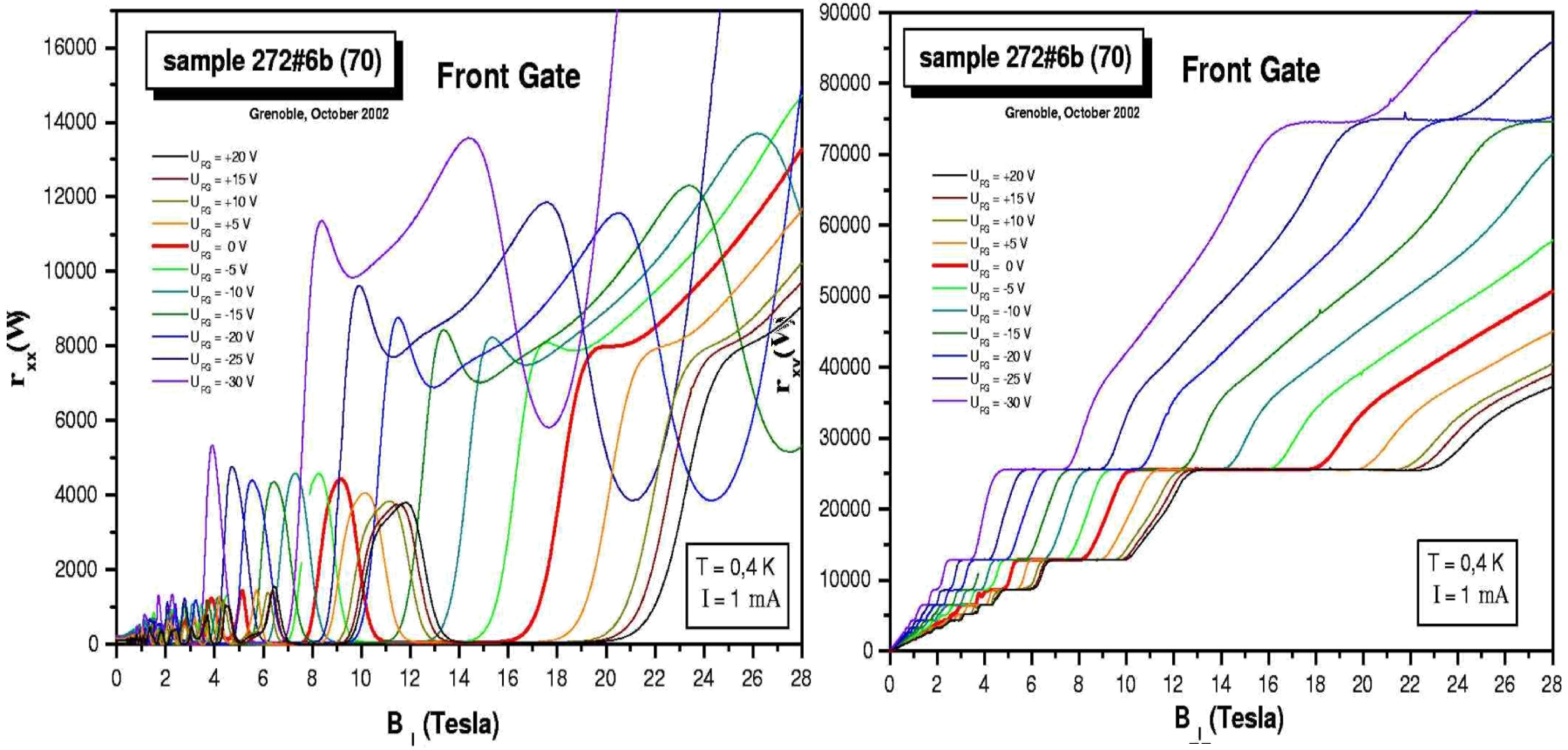




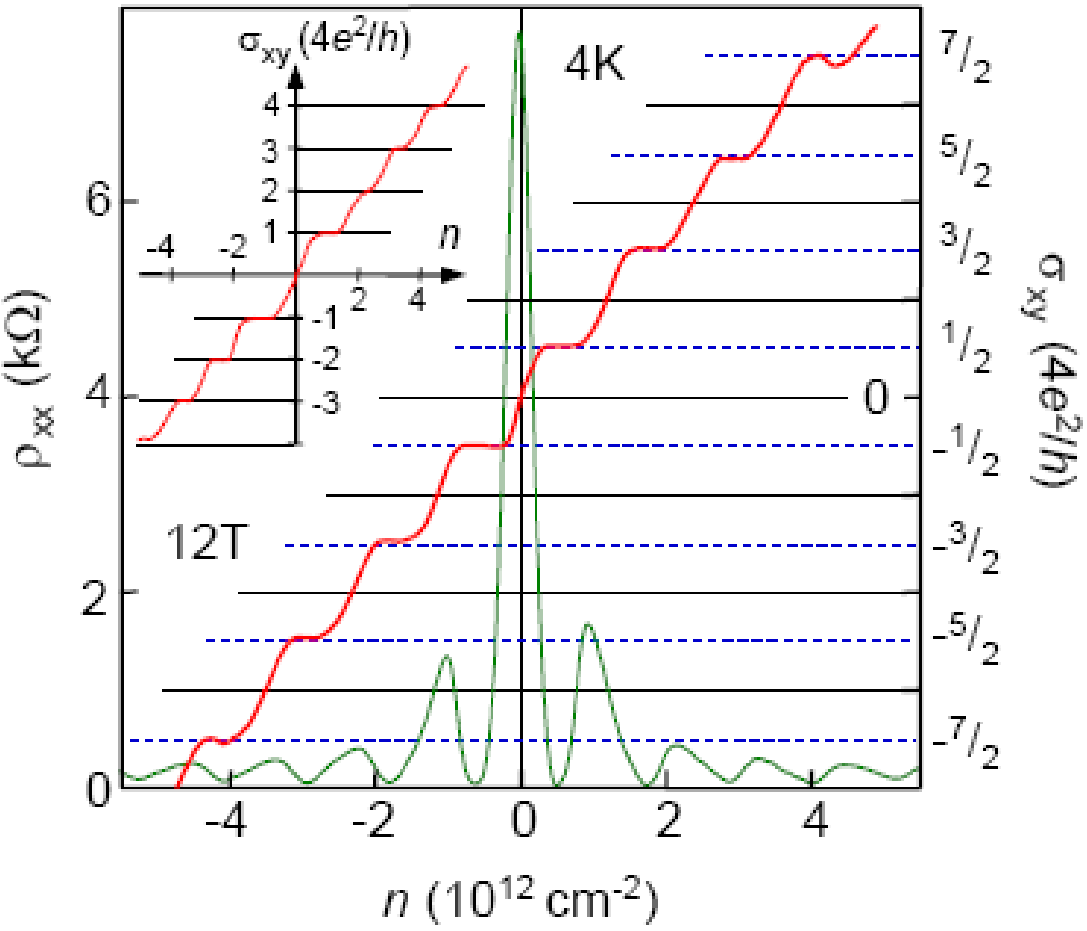
Schema vzorku pro transportní měření (elektronová litografie)



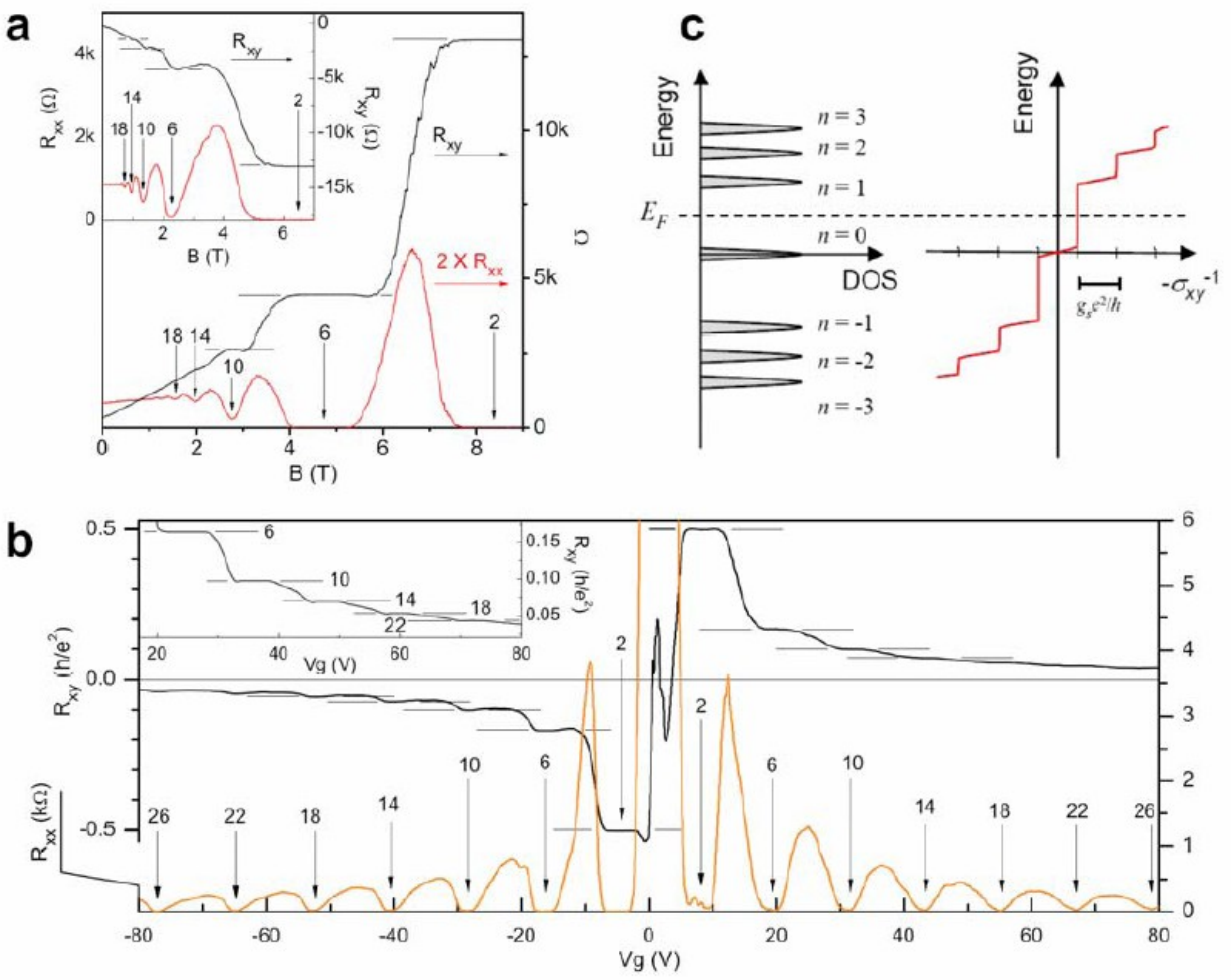
Hallův jev Schrodingerových elektronů



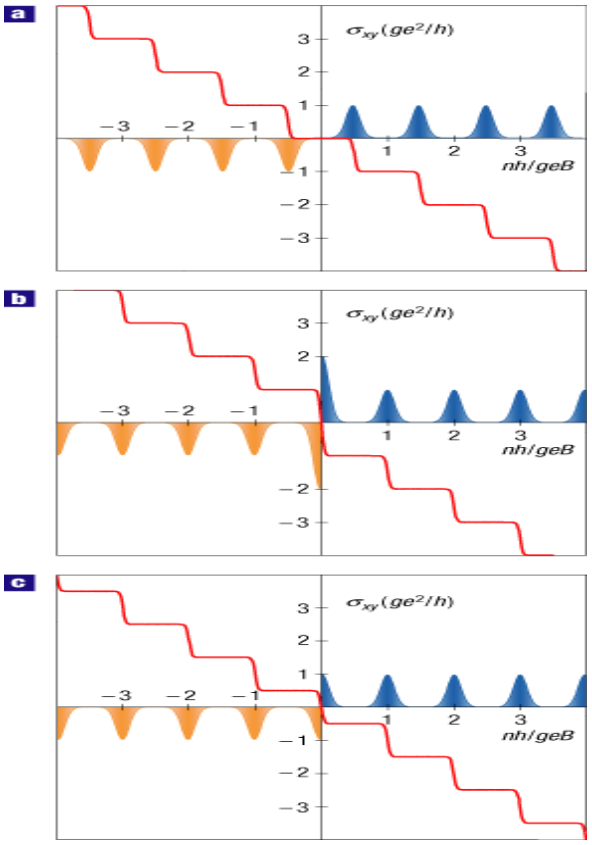
Poločíselný QHE v grafenu v závislosti na napětí



Měření na nejlepších vzorcích, závislost na magnetickém poli



QHE v závislosti na napětí

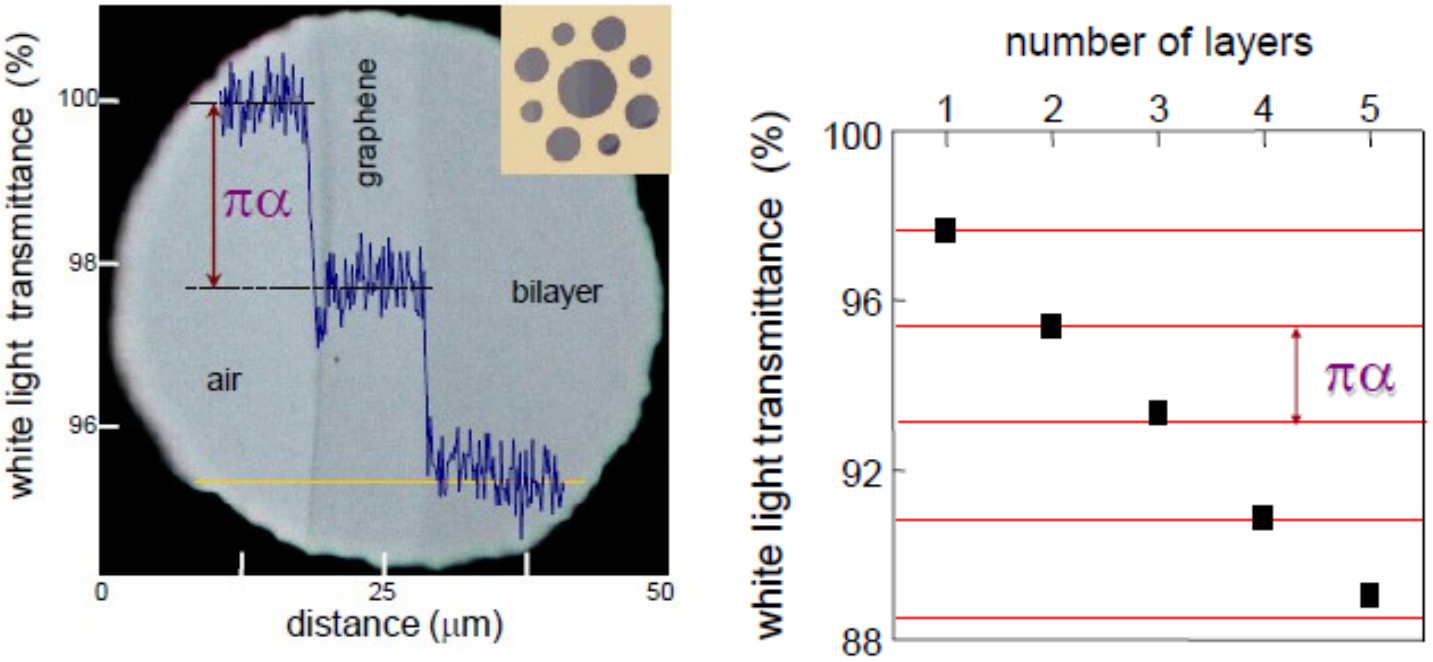


a) Standardní 2DEG

a) Bilayer graphene

a) Single layer graphene

Visualisation of fine structure constant



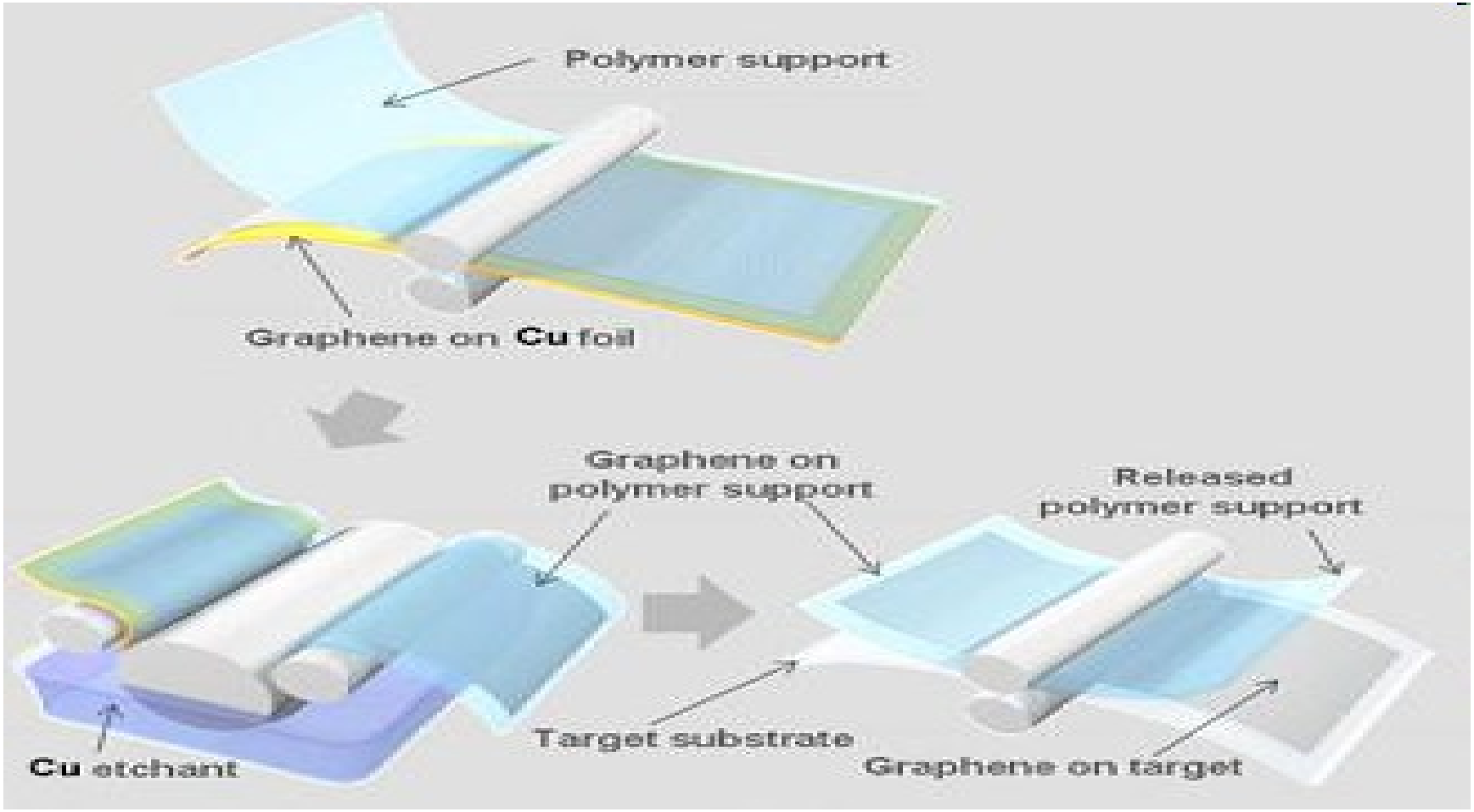
The fine structure constant observed "with a naked eye"

$\alpha = 1/137\ (\pm 2\%)$

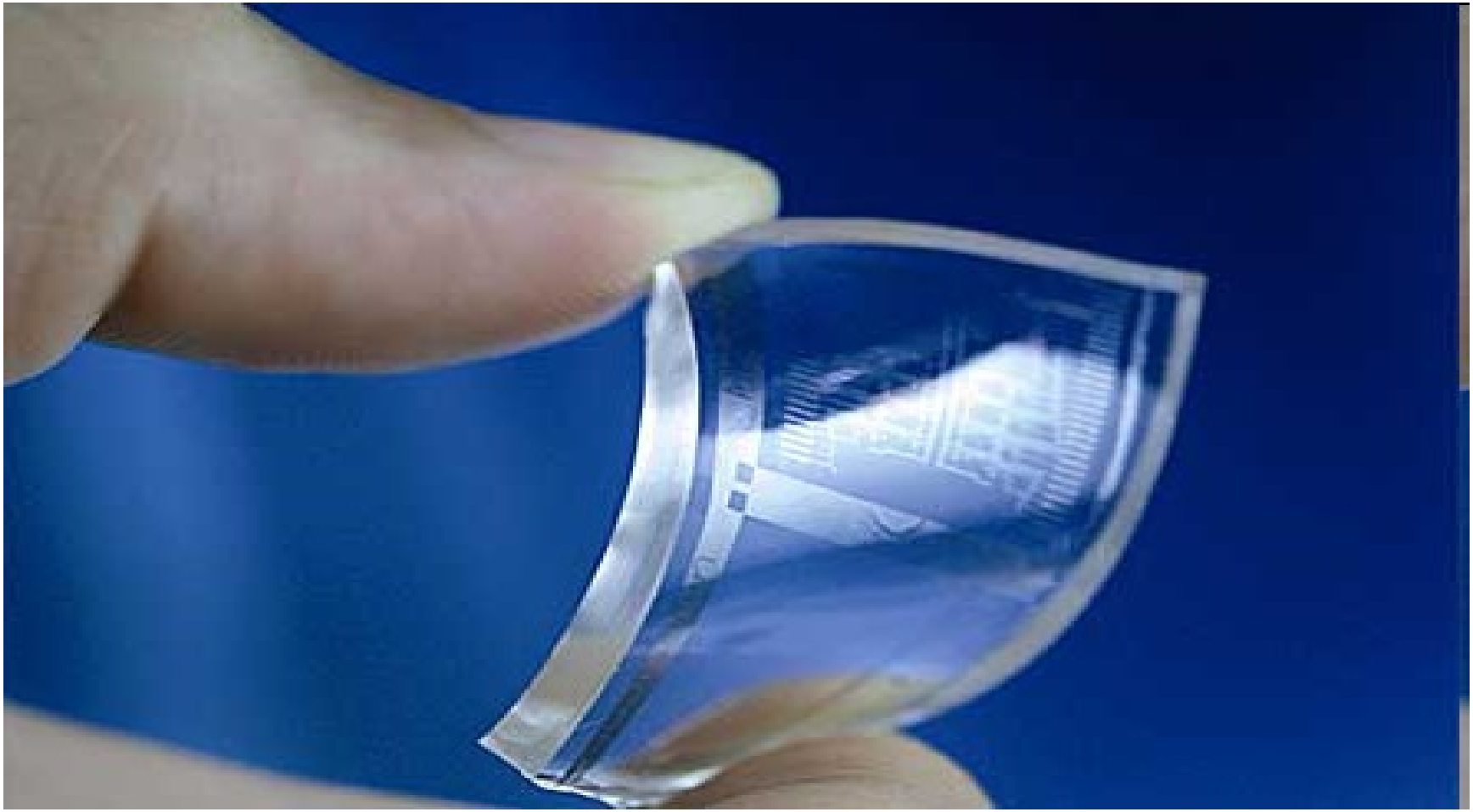
Příprava grafenu

Příprava grafenu depozicí na kov

M. Kalbáč UFCH JH



Folie s grafenem



Příprava grafenu na povrchu SiC

Epitaxial GrapheneLab - Georgia Institute of Technology

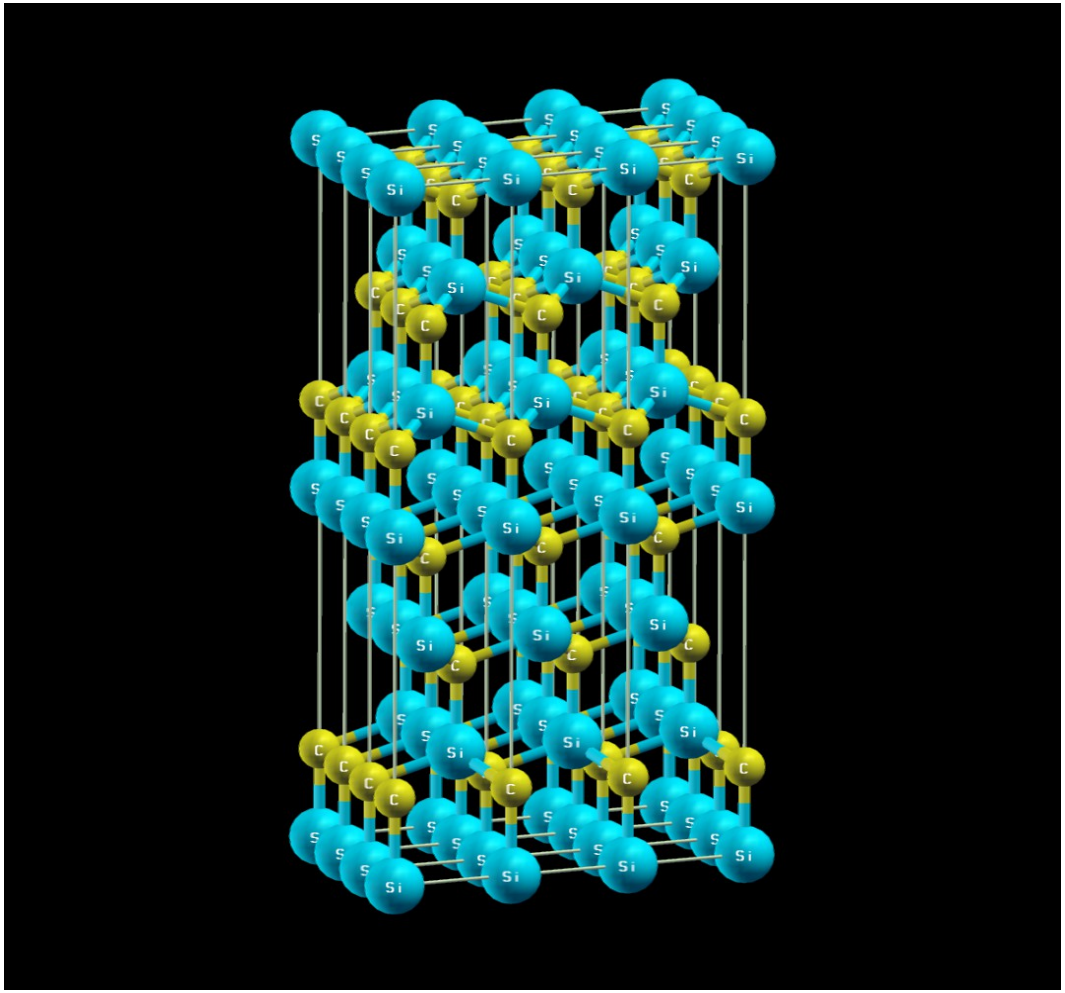
Nobel Laureate Albert Fert (center) is working with physicists Claire Berger and Walt de Heer (left to right)

Epitaxial Graphene Transistor (EPIGRAT)

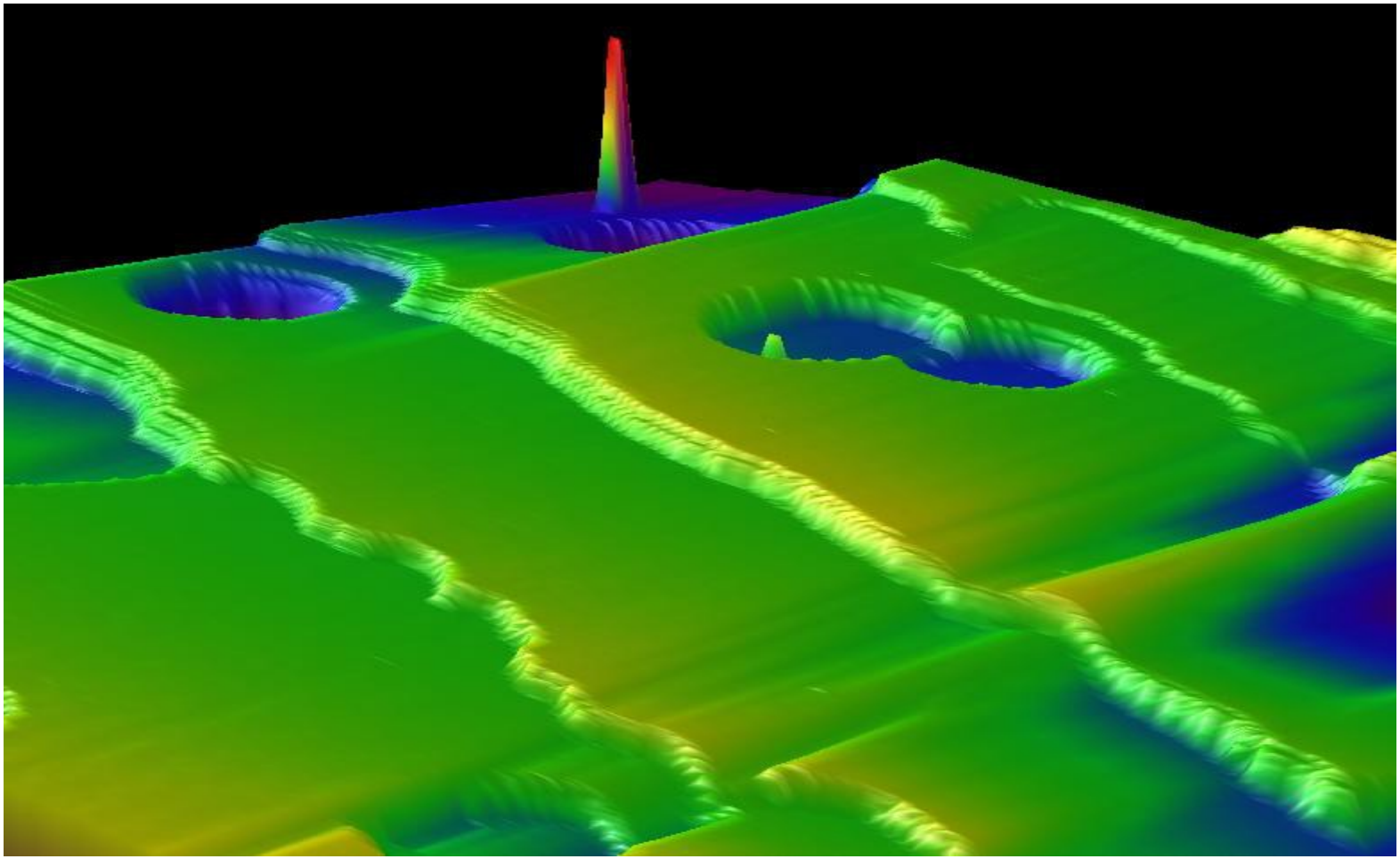
The aim of EPIGRAT is to synthesize and characterize epitaxial graphene layers on silicon carbide suitable for future electronics using different growth techniques, and to develop and characterize high frequency transistors made from these materials.

Švédsko, Polsko, Turecko, Francie a Česká republika

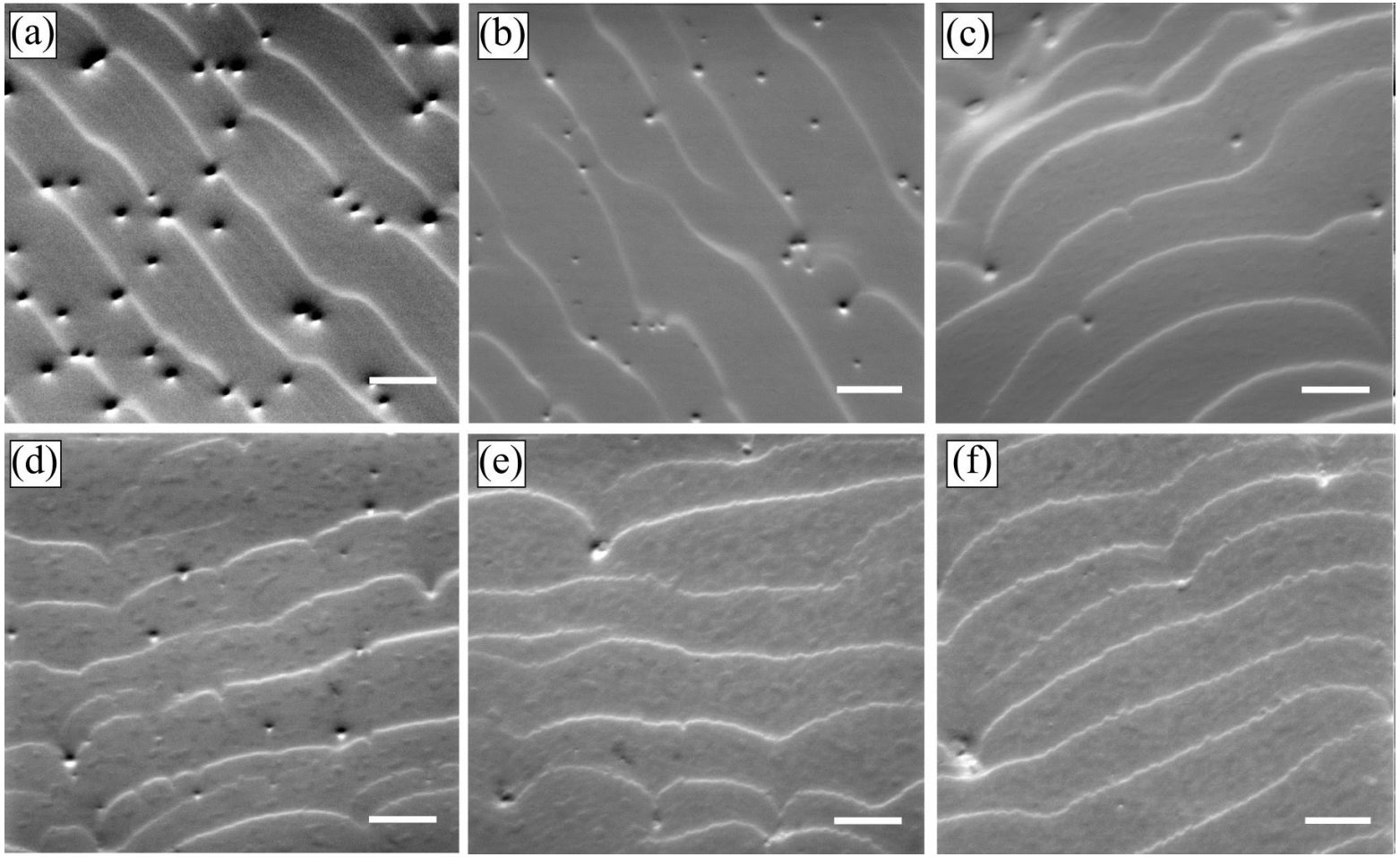
SiC crystal structure



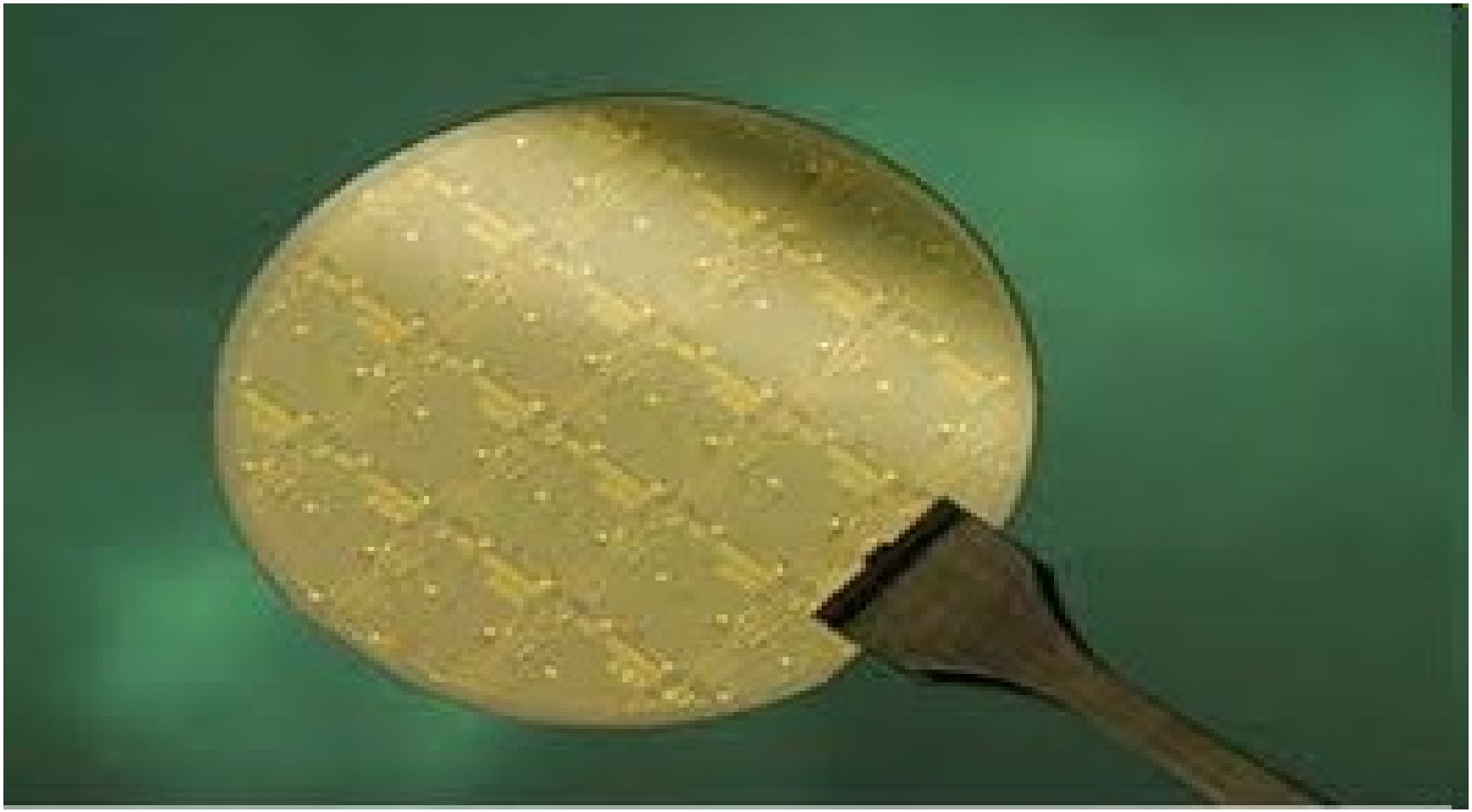
Povrch SiC



Příprava grafenu na karbidu křemíku

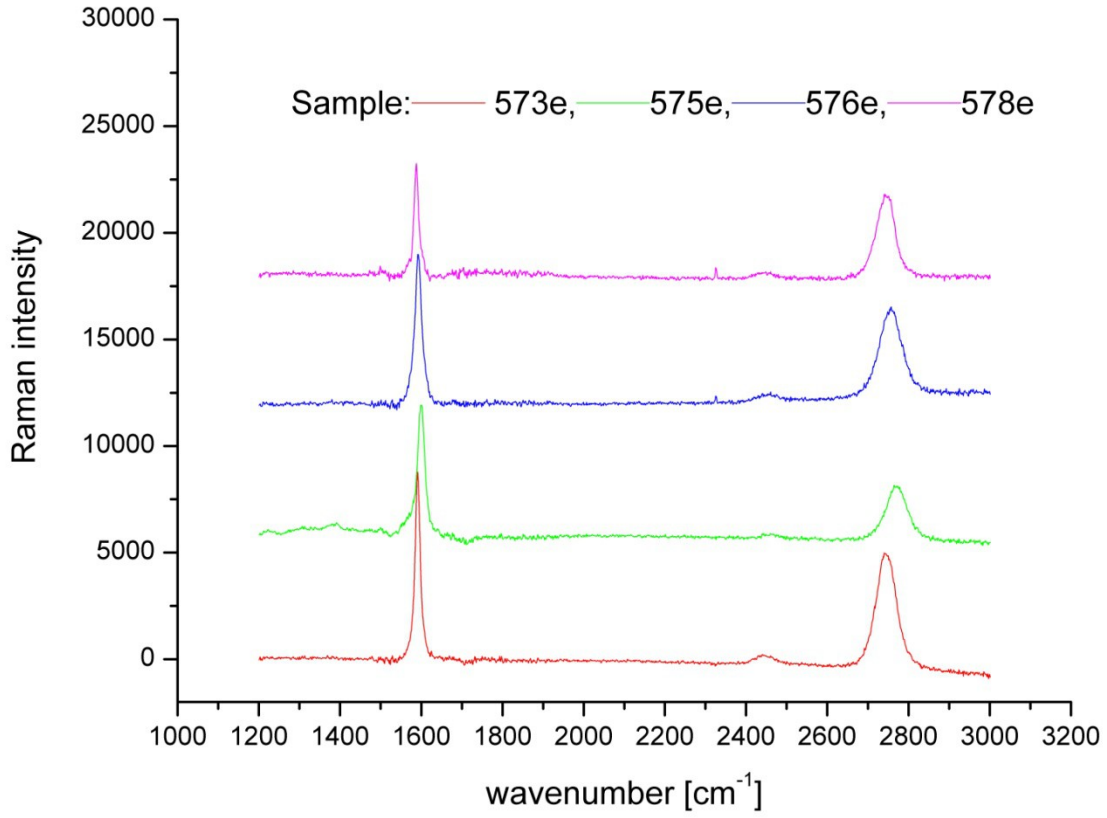


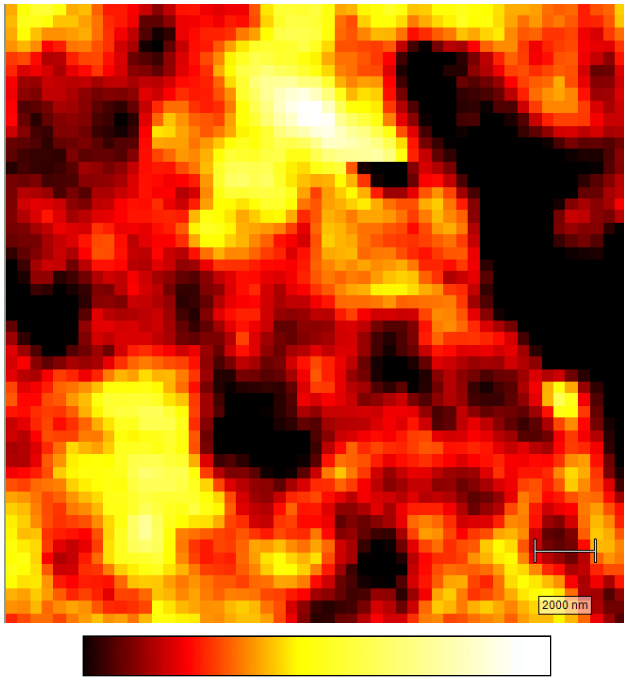
Grafen na podložce SiC



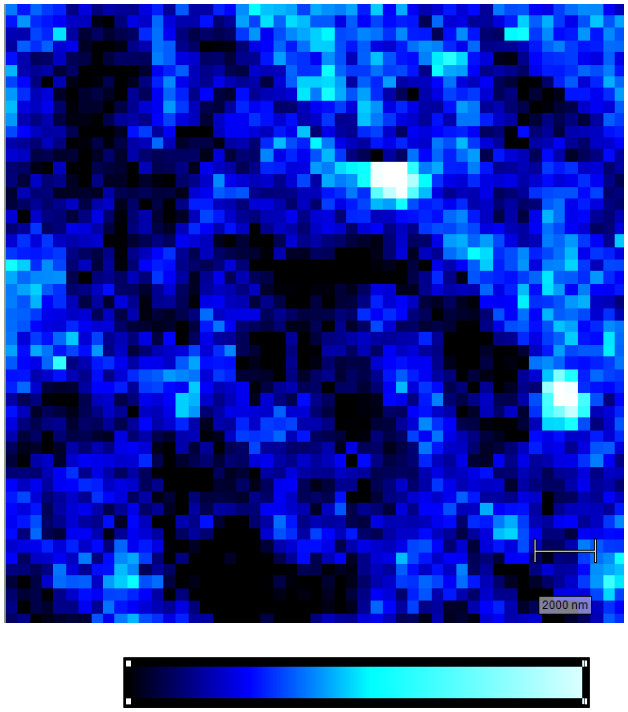
Ramanova spektra grafenu na SiC

M. Ledinský FZU



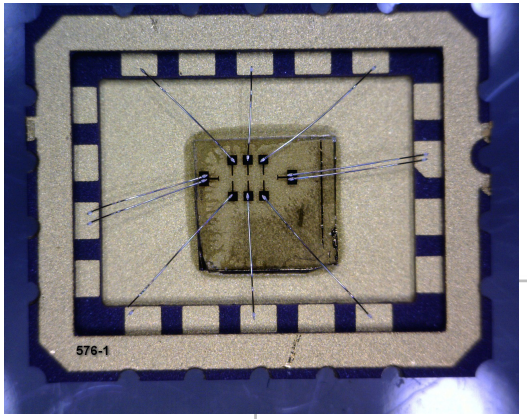


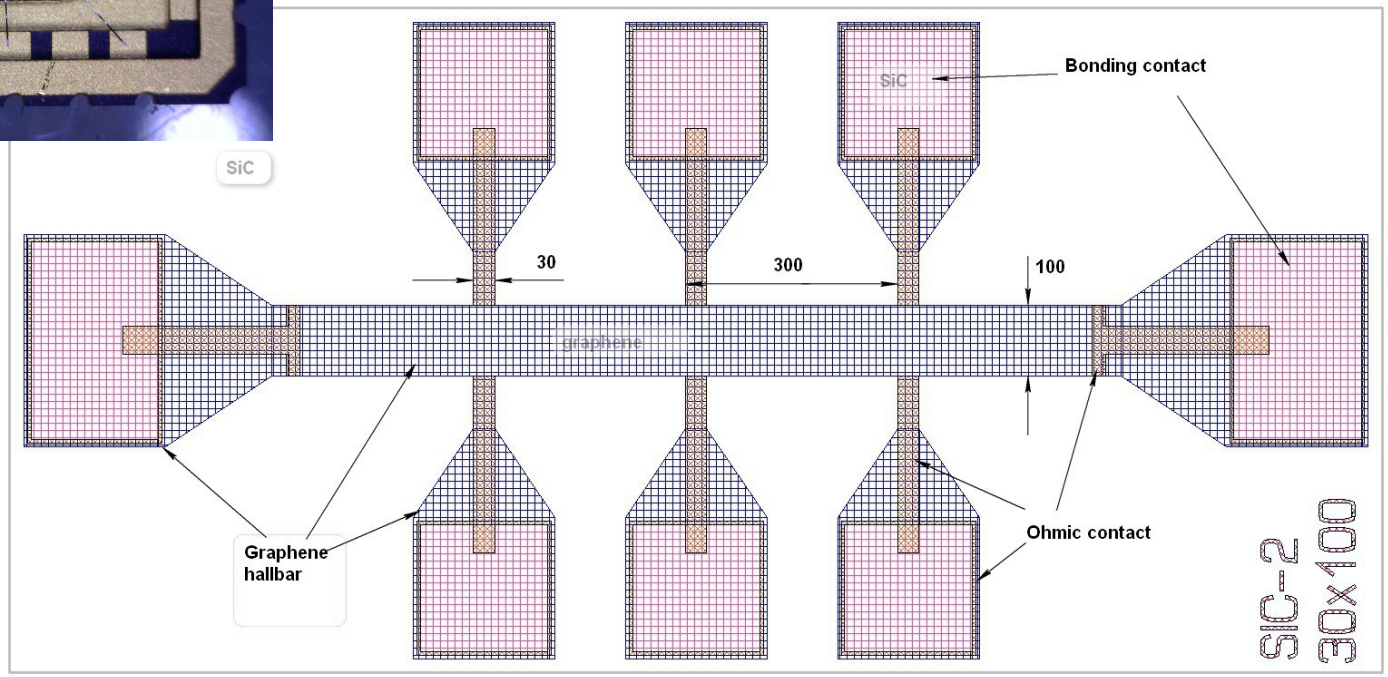
lokální napětí



poruchy

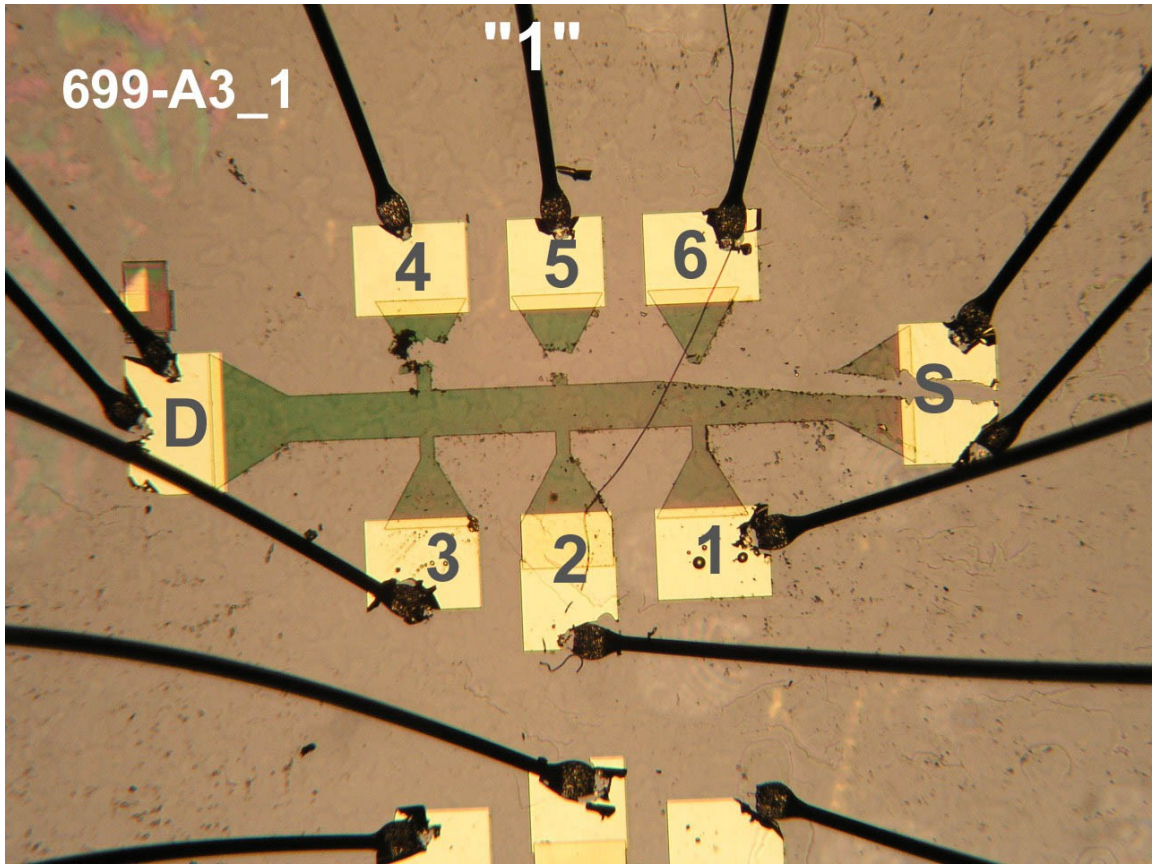
Lithography-the layout of the device



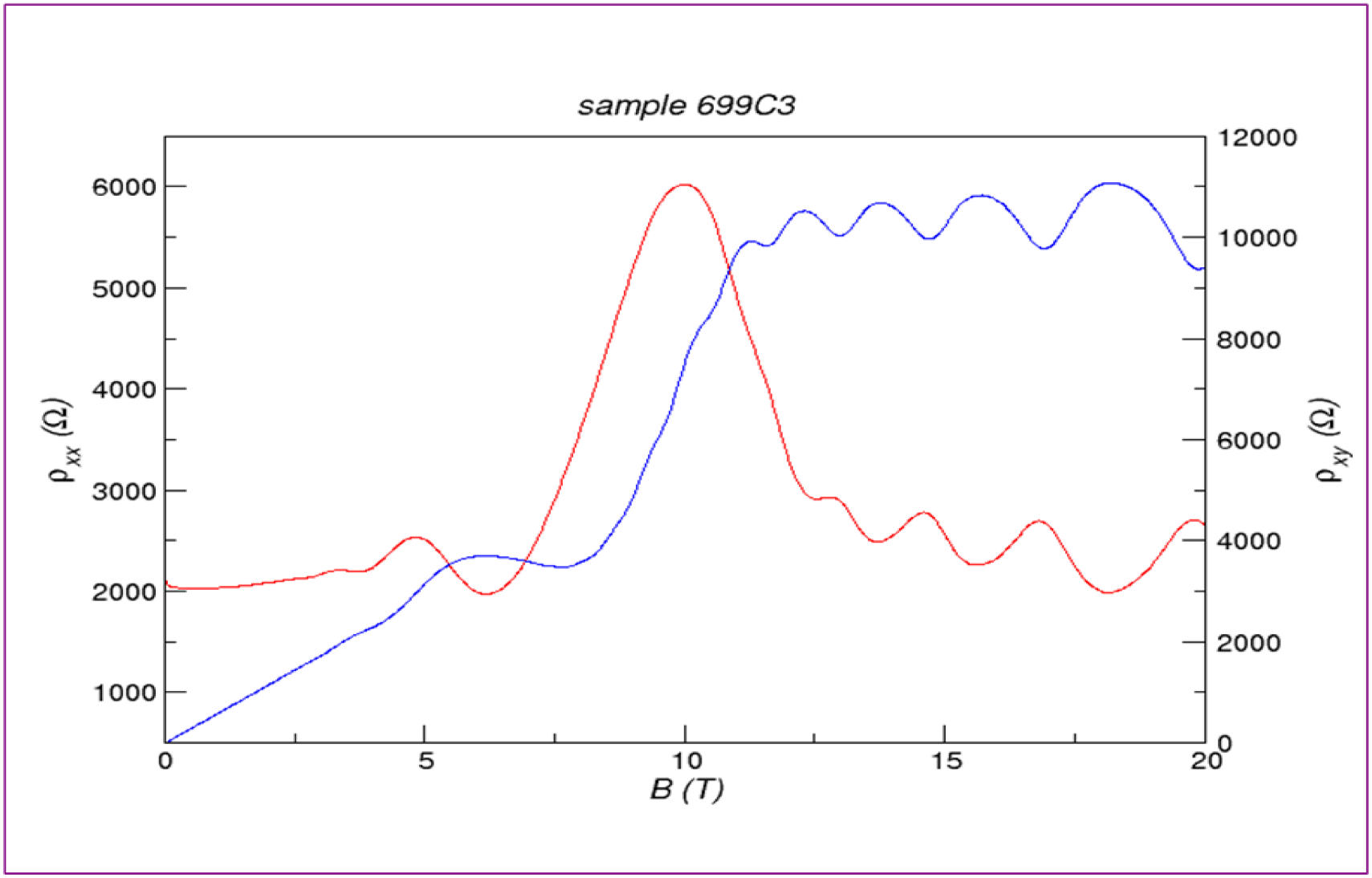


Grenoble december 2010

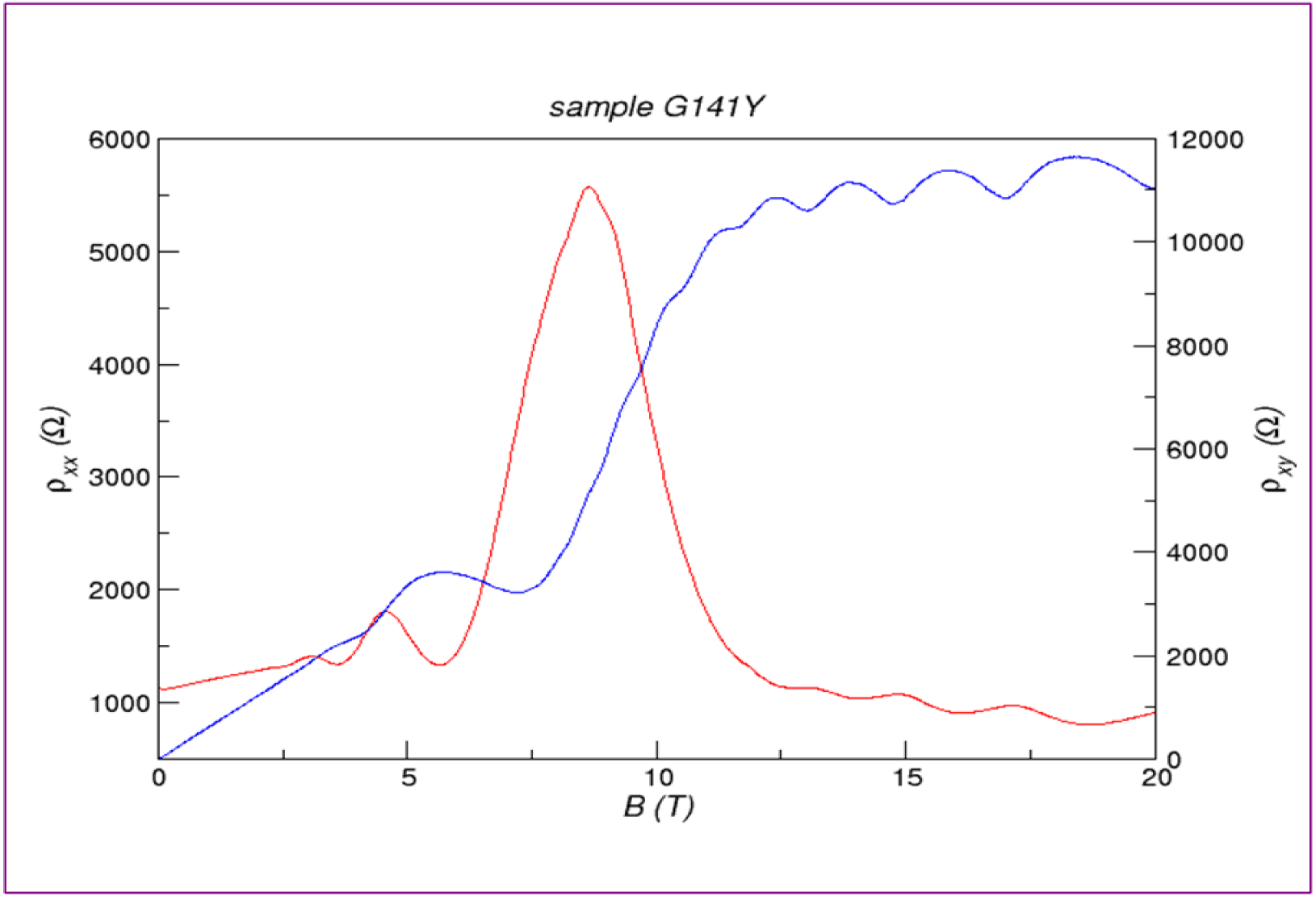
Real sample...



The sample 699: longitudinal and Hall magnetoresistances. Origin ITME Warsaw, Poland

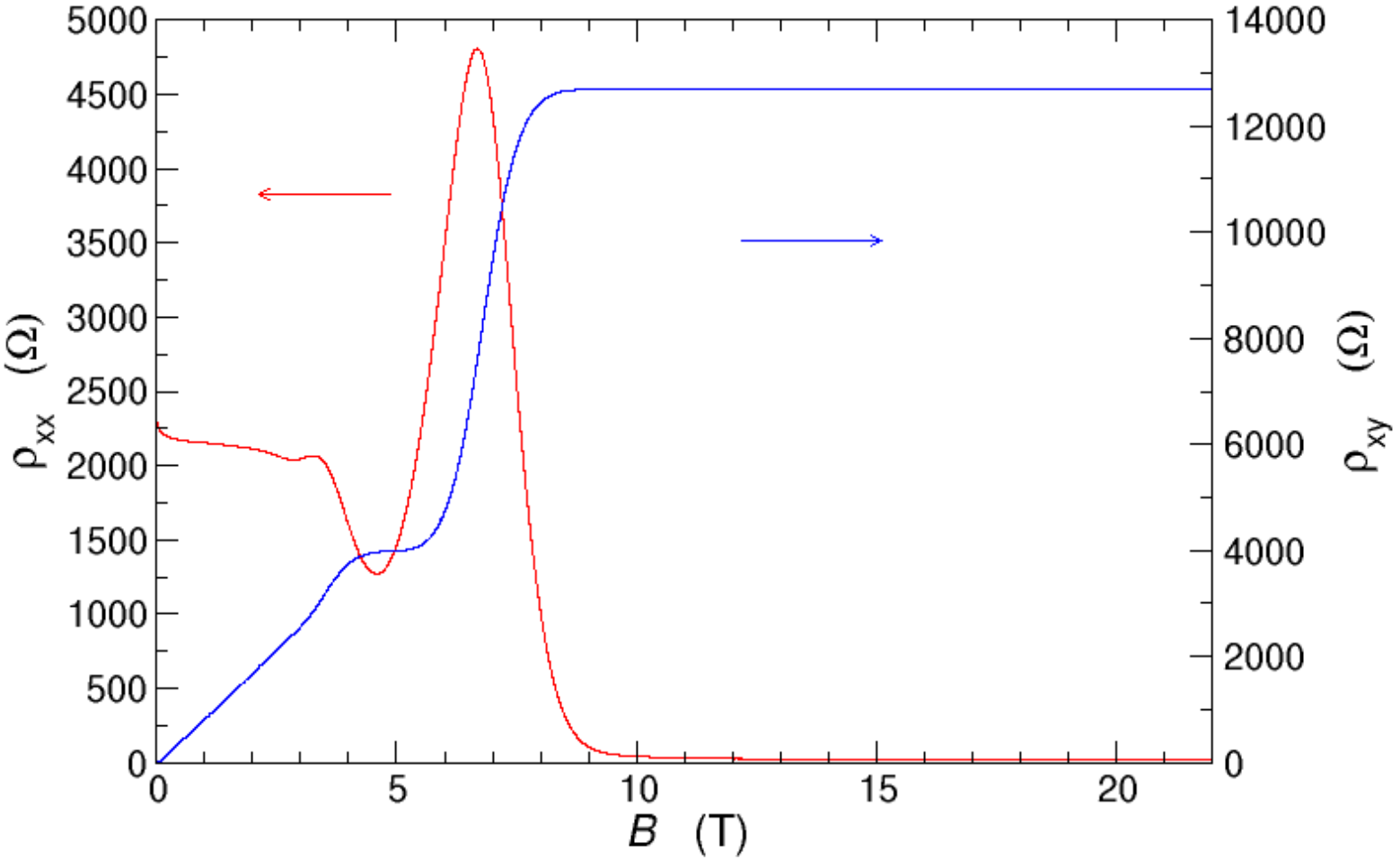


The sample 141: longitudinal and Hall magnetoresistances. Origin Linköping University.



Grenoble april 2012

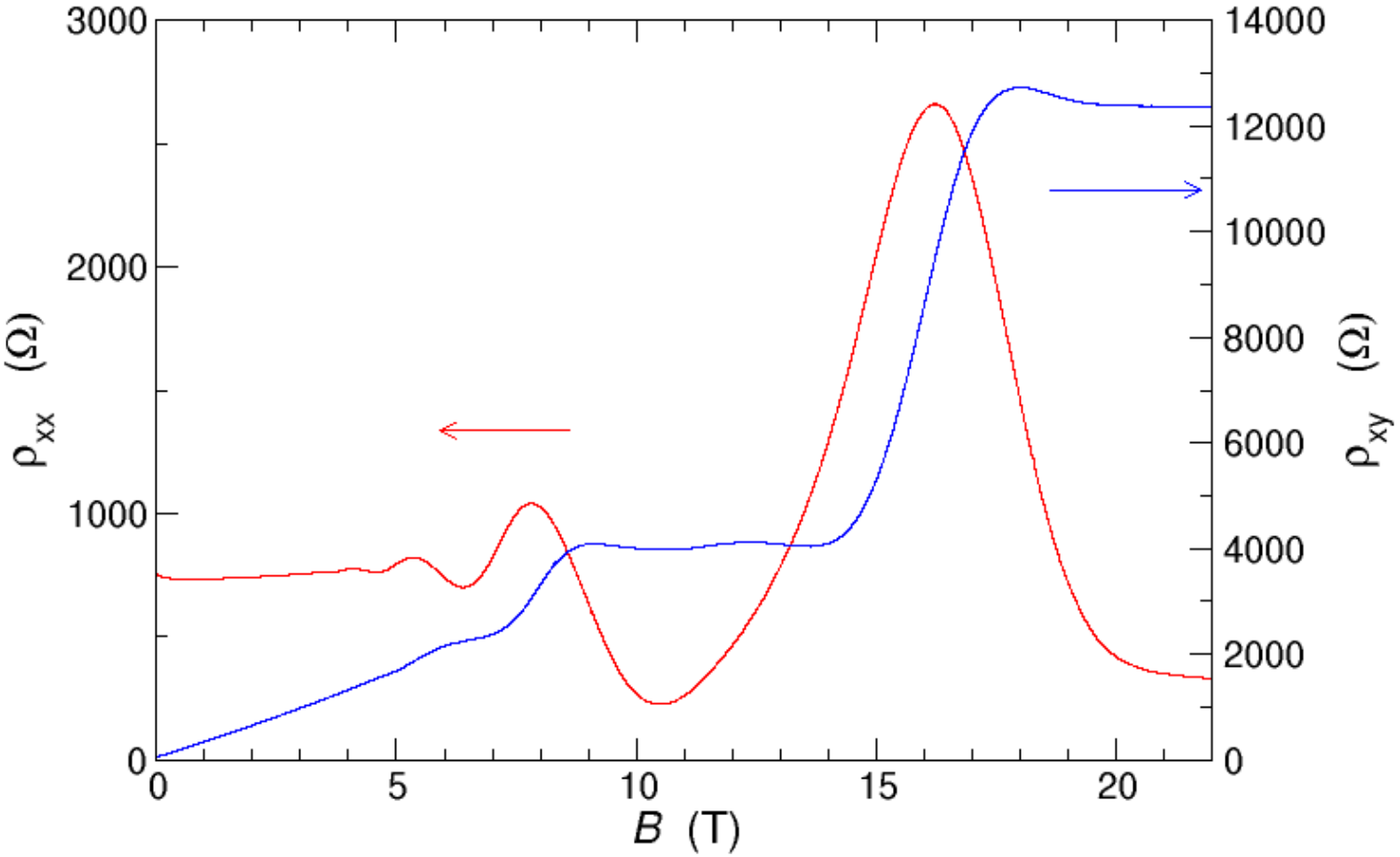
The sample 9052: longitudinal and Hall magnetoresistances. Origin ITME Warsaw, Poland



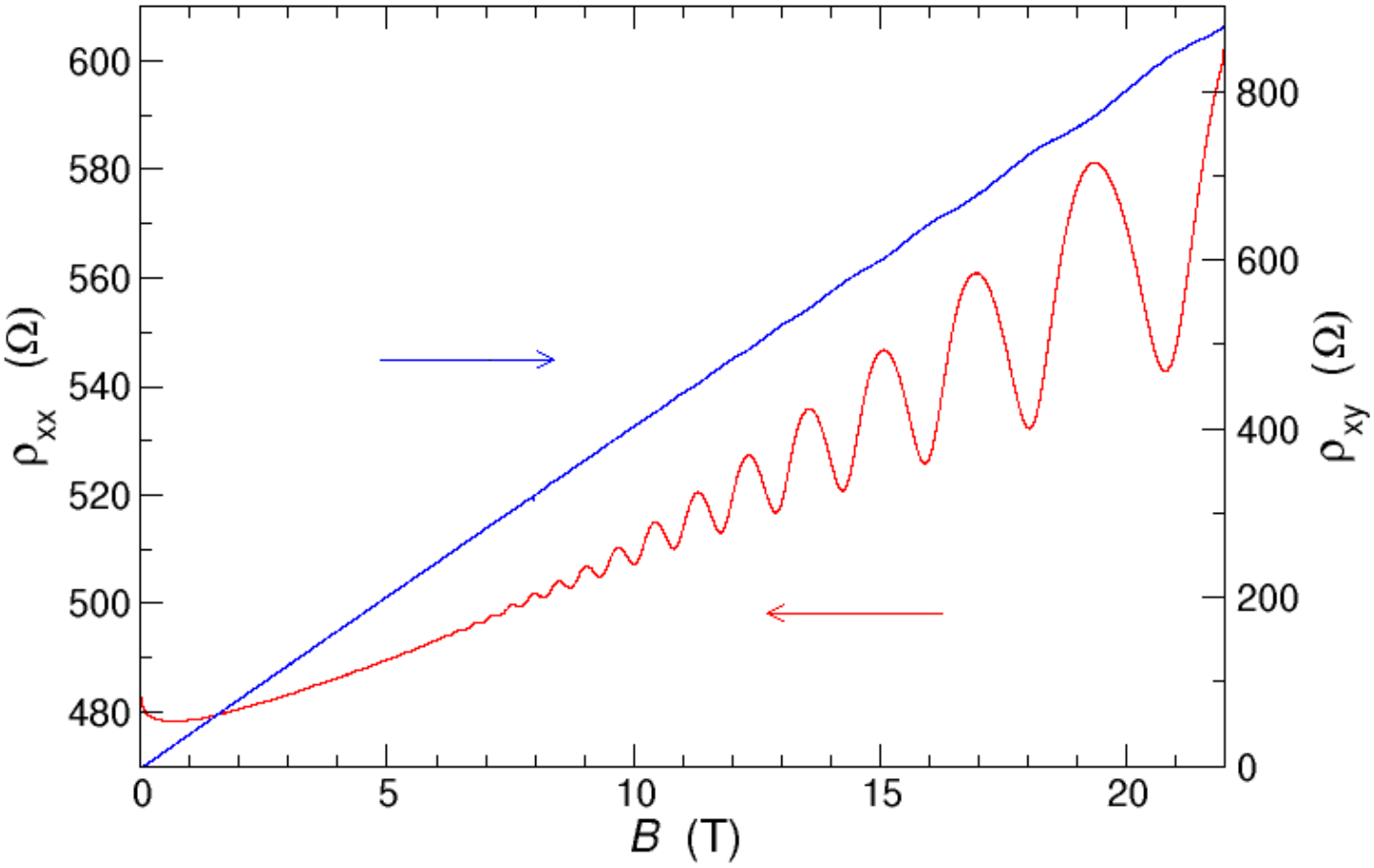
$N_{SdH} = 9.69 \times 10^{11} cm^{-2}$, $N_H = 7.24 \times 10^{11} cm^{-2}$, $\mu_H = 3.89 \times 10^3 \, cm^2/V \cdot sec.$

Influence of samples hydrogenation

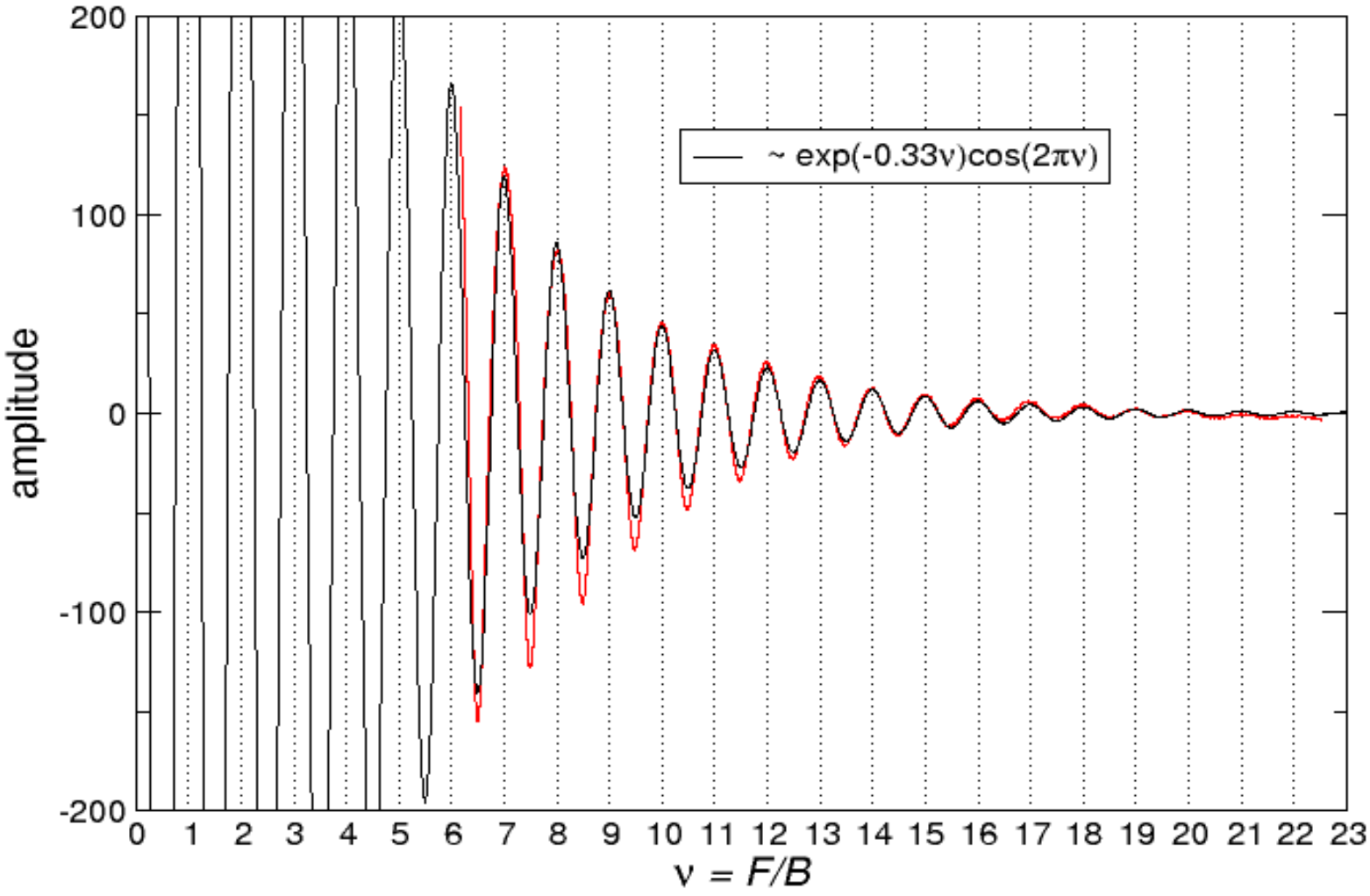
The sample 575: longitudinal and Hall magnetoresistances. Origin Linköping University, Sweden.



The sample 576: longitudinal and Hall magnetoresistances. Origin Linköping University, Sweden.

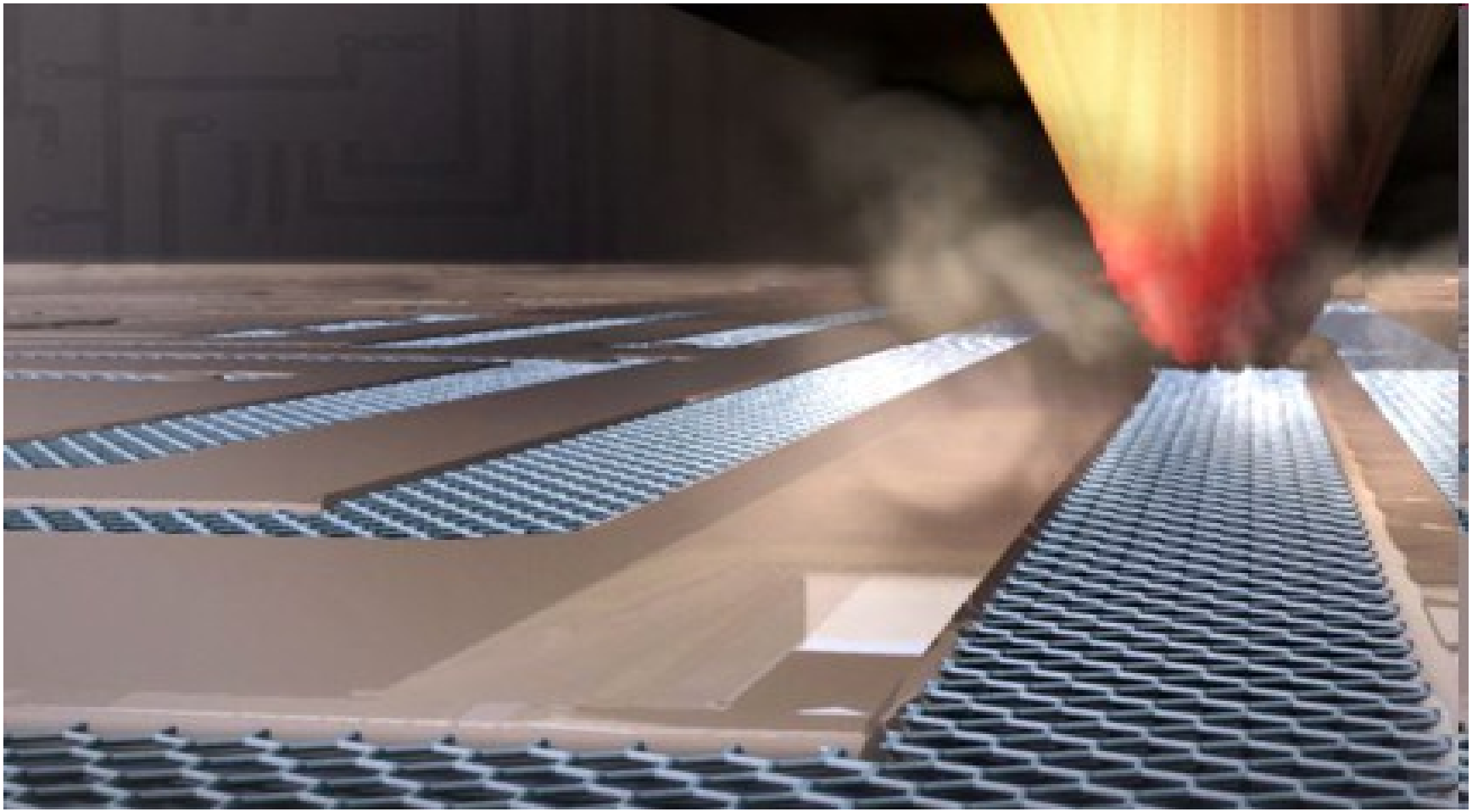


The sample 576: the oscillatory part of ρ_{xx} is compared with the oscillatory part of DOS of Dirac fermions.



Praktické aplikace

Grafenová mikroelektronika



Možné aplikace grafenu

- hodinky / kalendáře
- ohebný světelný panel
- elektronický papír
- mobilní telefony
- elektronické platby
- dotykové displeje,
- mikroelektronika
- kompozitní materiály
- přenosné počítače
- elektrody fotovoltaických článků

Pramen: denní tisk

KONEC