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Graphene on Silicon Carbide: a laboratory for basic principles of solid state physics

Heiko B. Weber
Chair for Applied Physics
Friedrich-Alexander-Universität Erlangen-Nürnberg

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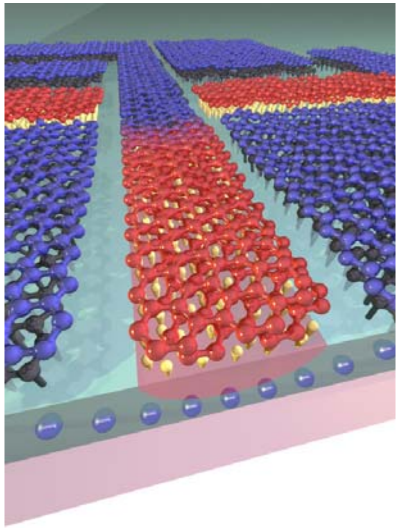
Epitaxial graphene on SiC

Physics in the graphene plane

The graphene/SiC system: a Schottky junction

Physics in SiC: Colour centres



Silicon carbide

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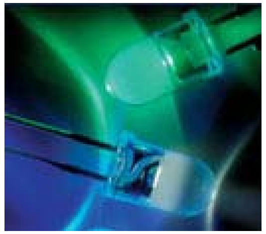
Abrasive

Jewel



Substrate for GaN LEDs

Silicon carbide as electronic material

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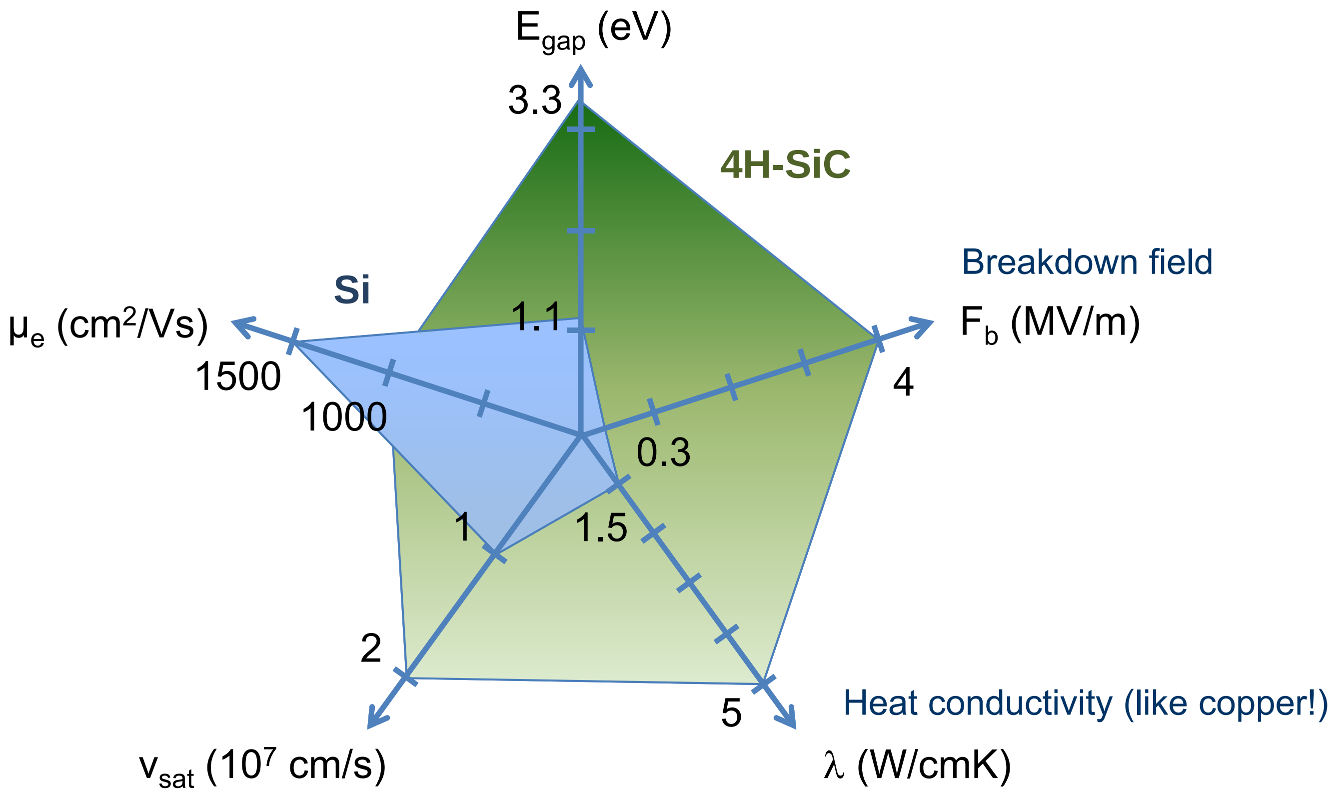
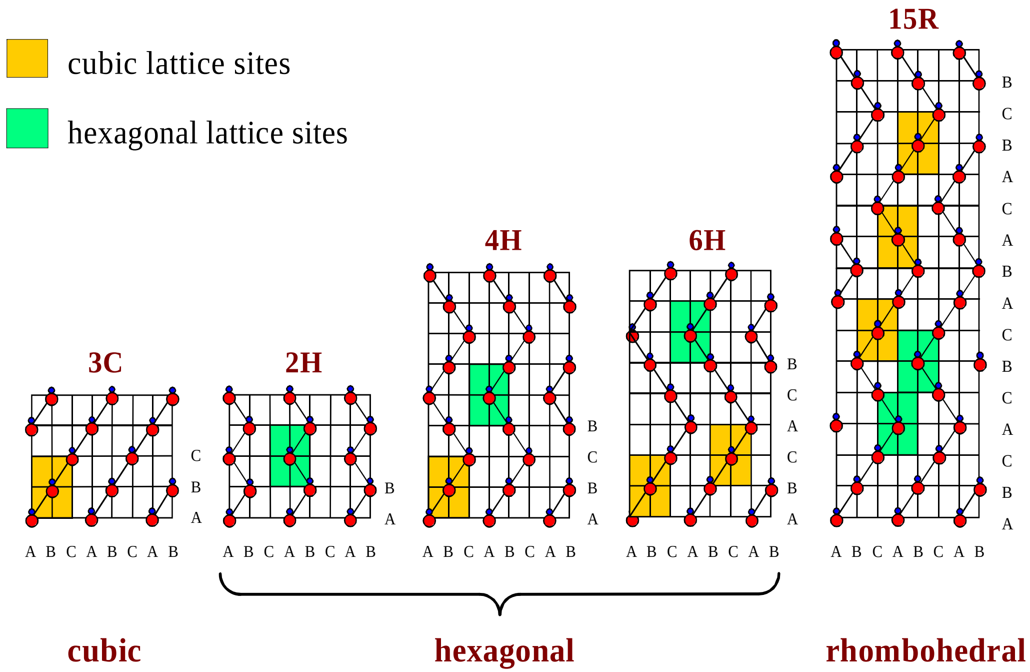


SiC polytypes



band gap energy at RT (eV)

2.3 **3.35** **3.28** **3.08** **3.03**

Silicon carbide for high power electronics

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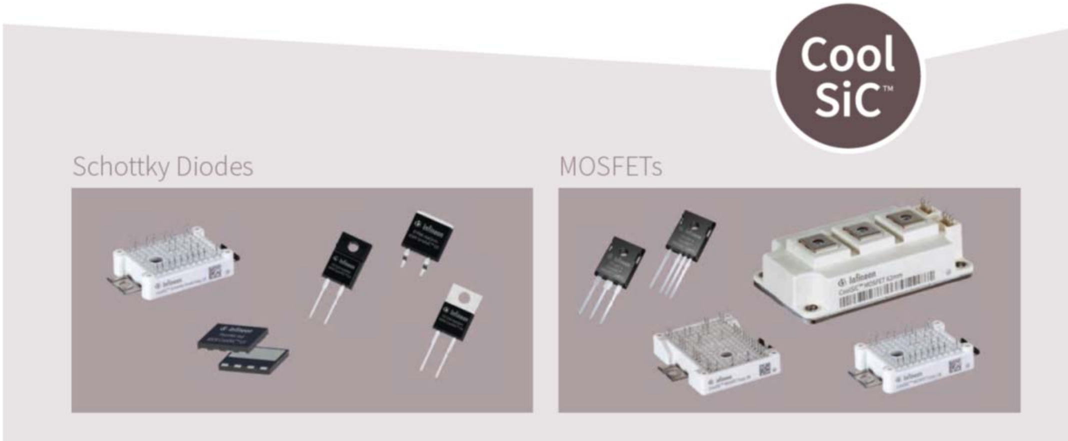
Cree power MOSFET

Blocking Voltage	1700 V
Current Rating At 25°C	72 A
$R_{ds(on)}$ At 25°C	45 mΩ
Package	TO-247-3
Total Switching Energy Loss	3 mJ
Gate Charge Total	188 nC
Maximum Junction Temperature	150 °C
Lead-frame Materials	100% matte, tin solder finish over a copper lead frame

30 years of research @ LAP:

Emphasis on point defects

Dr. Michael Krieger



Infineon power Diodes and MOSFETs

Decomposition of 4H / 6H SiC

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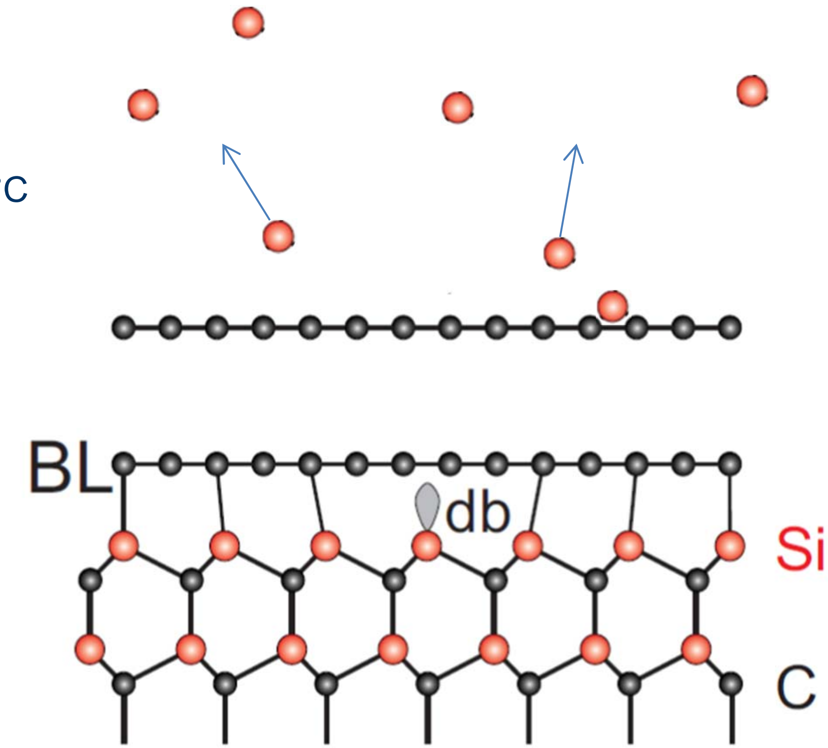
At ~ 1700°C

in Argon



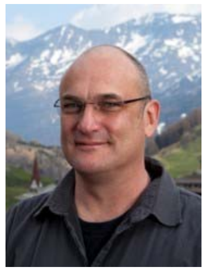
Graphene

Buffer layer

→ High quality graphene on semiconductor wafers

Emtsev…H.B.Weber, T. Seyller:

Nature materials **8,** 203 (2009)



Thomas Seyller

Two materials on 4H/6H-SiC

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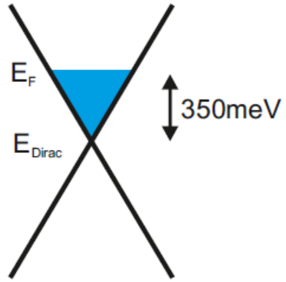
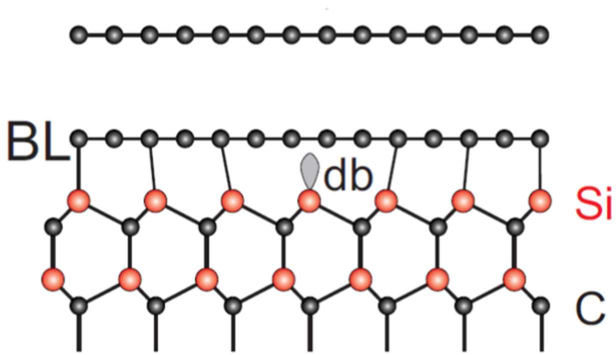
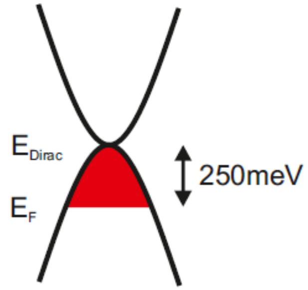
Monolayer graphene (MLG)

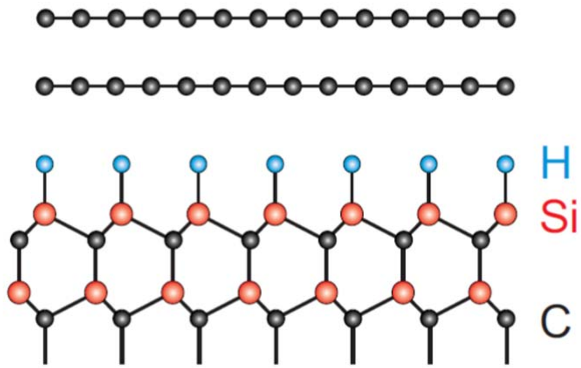




K. Emtsev…H.B.Weber, T. Seyller: Nature materials **8,** 203 (2009)

Quasi-free standing bilayer graphene (QFBLG)





Riedl et al. PRL 103, 246804 (2009); F. Speck, …H.B.Weber, T. Seyller, APL 99, 122106 (2011)

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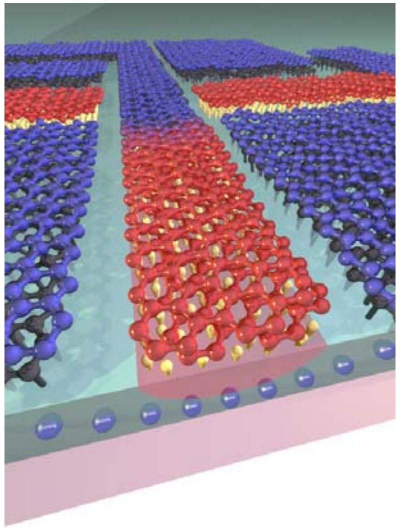
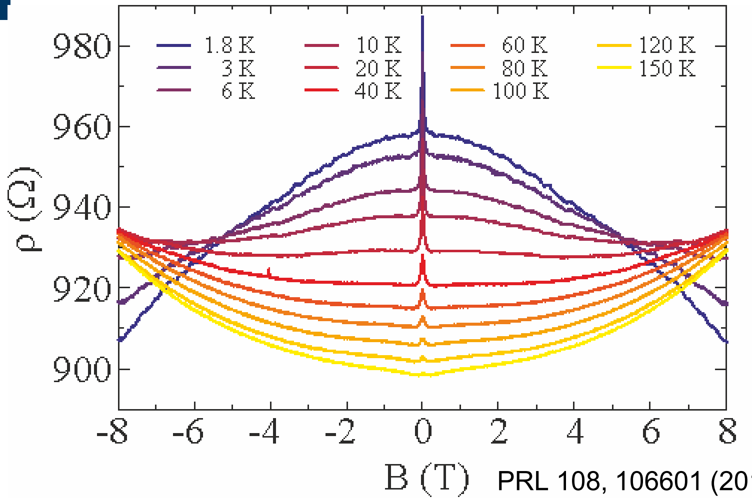


Magnetoresistance of large-area graphene

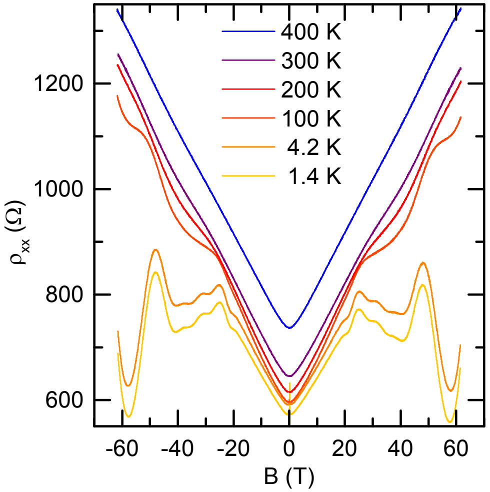
Graphene monolayer



PRL 108, 106601 (2012)

Nature physics 8,352 (2012)

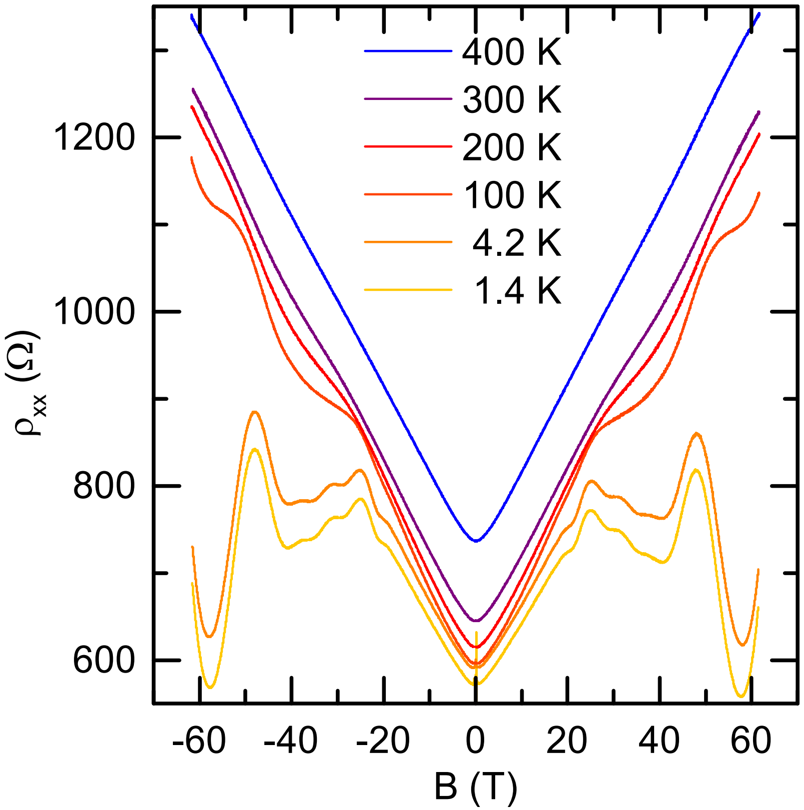
Graphene bilayer



Nature physics 11,650 (2015)

Nature communications (2016) with Krstic

Non-saturating linear magnetoresistance



High magnetic field Laboratory Rossendorf

Simple questions

Question:

Can we understand linear magnetoresistivity ?

Nonsaturating linear Magnetoresistance

… a long-standing enigma in solid state physics …

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Experimentally observed ever since
in disordered conductors

- Kapitza 1929
- Potassium PRB 4, 1134 (1971)

- 3D Silver chalcogenides
  - Nature 390, 57 (1997)
  - Nature 417, 421 (2002)
  - PRL 88, 066602 (2002)
- 3D Silicon
  - Nature 457, 1112 (2009)
  - Scientific reports (2012)
- graphene-like materials
  - Nano letters 10, 3962 (2010)
  - Europhy. Lett. 94, 57004 (2011)
- Topological insulators
  - APL 102, 012102 (2013)
  - PRL 108, 266806 (2012)

Graphite

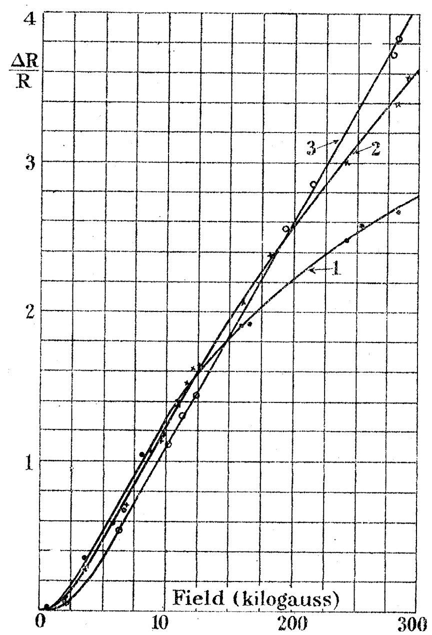

FIG. 17.—Graphite H ⊥ I.

Curve 1—Temperature of Liquid Air.
Curve 2—Temperature of Solid CO_2 and Ether.
Curve 3—Room Temperature.

Kapitza 1929

Linear magnetoresistance in segmented samples

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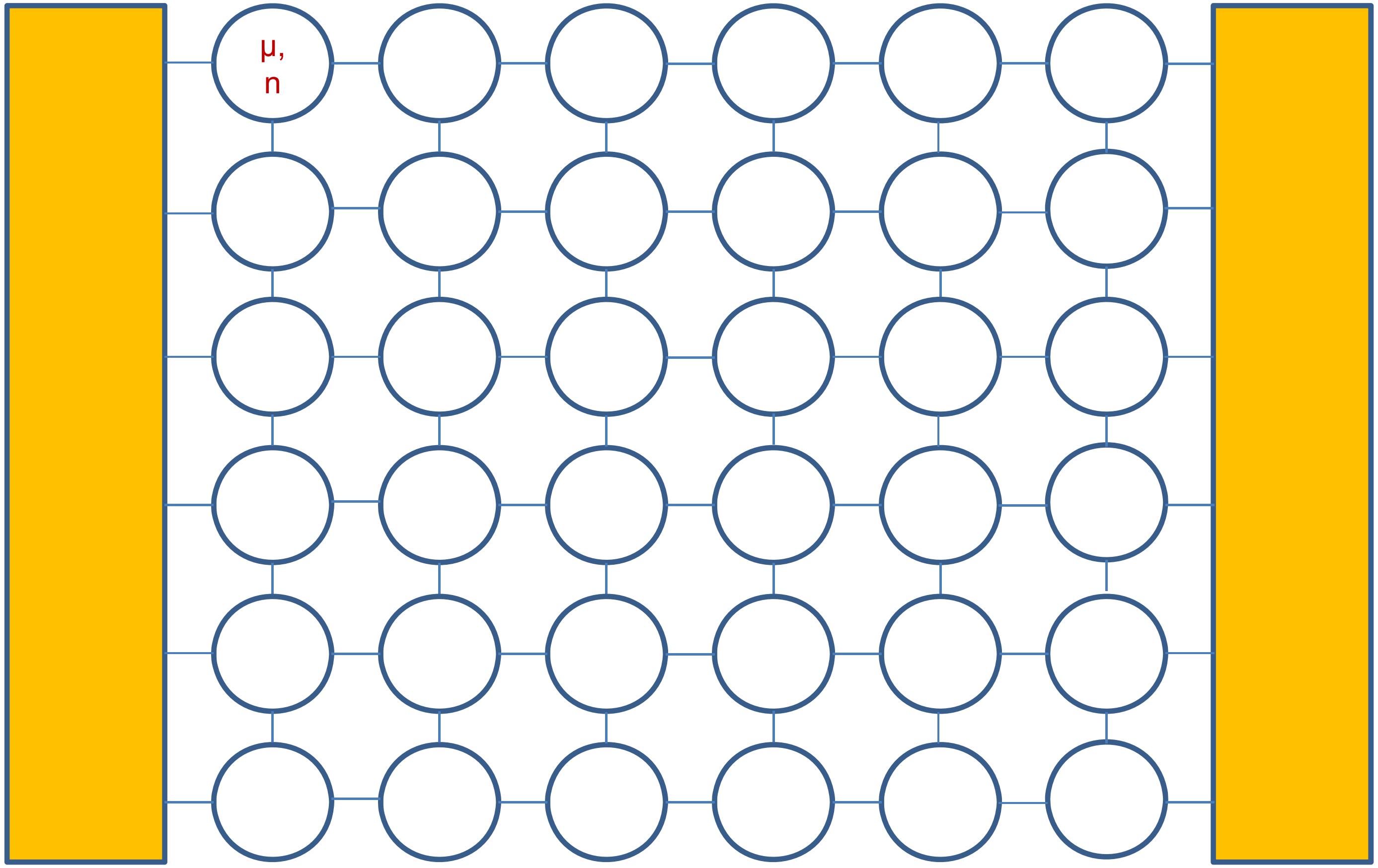
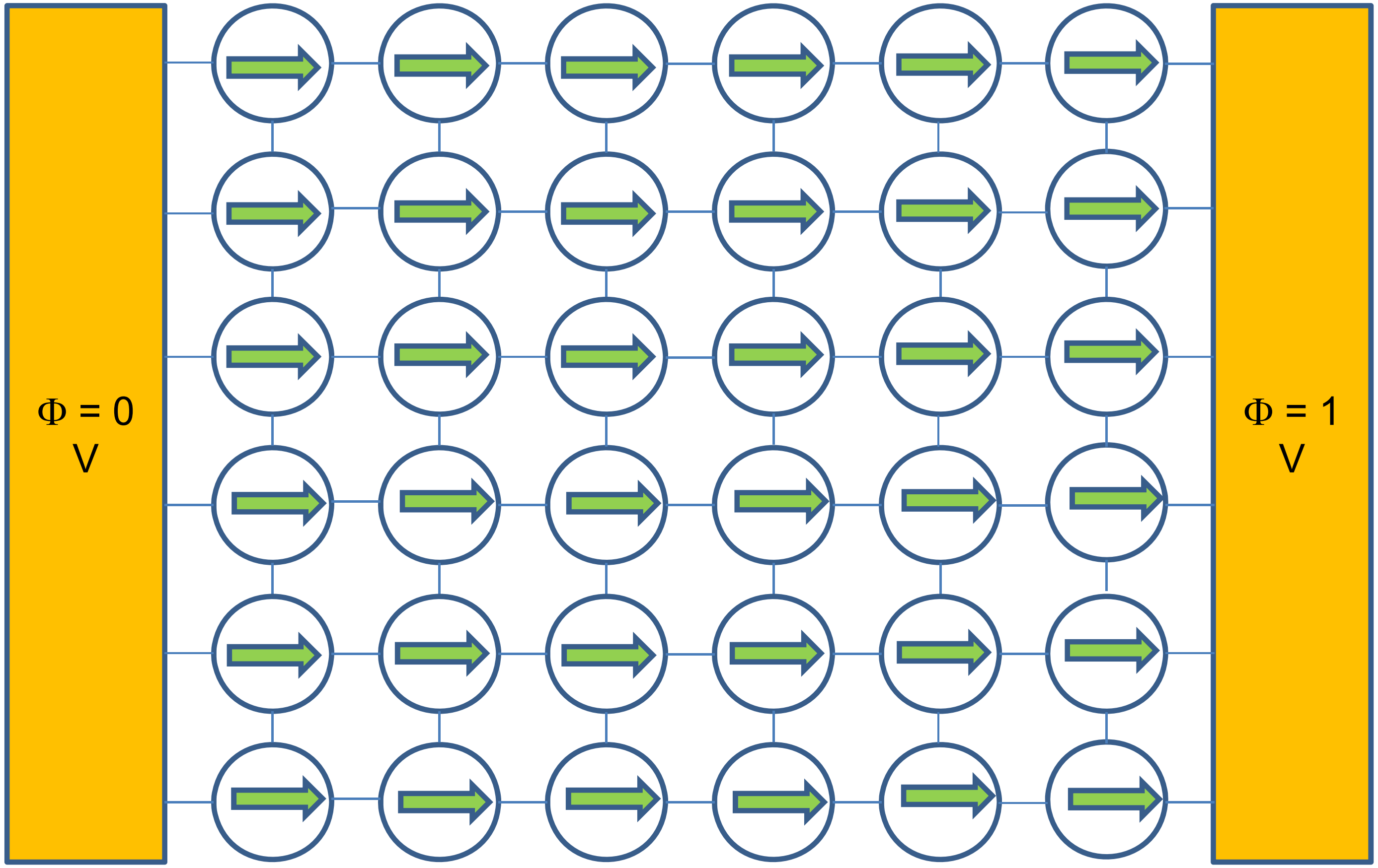
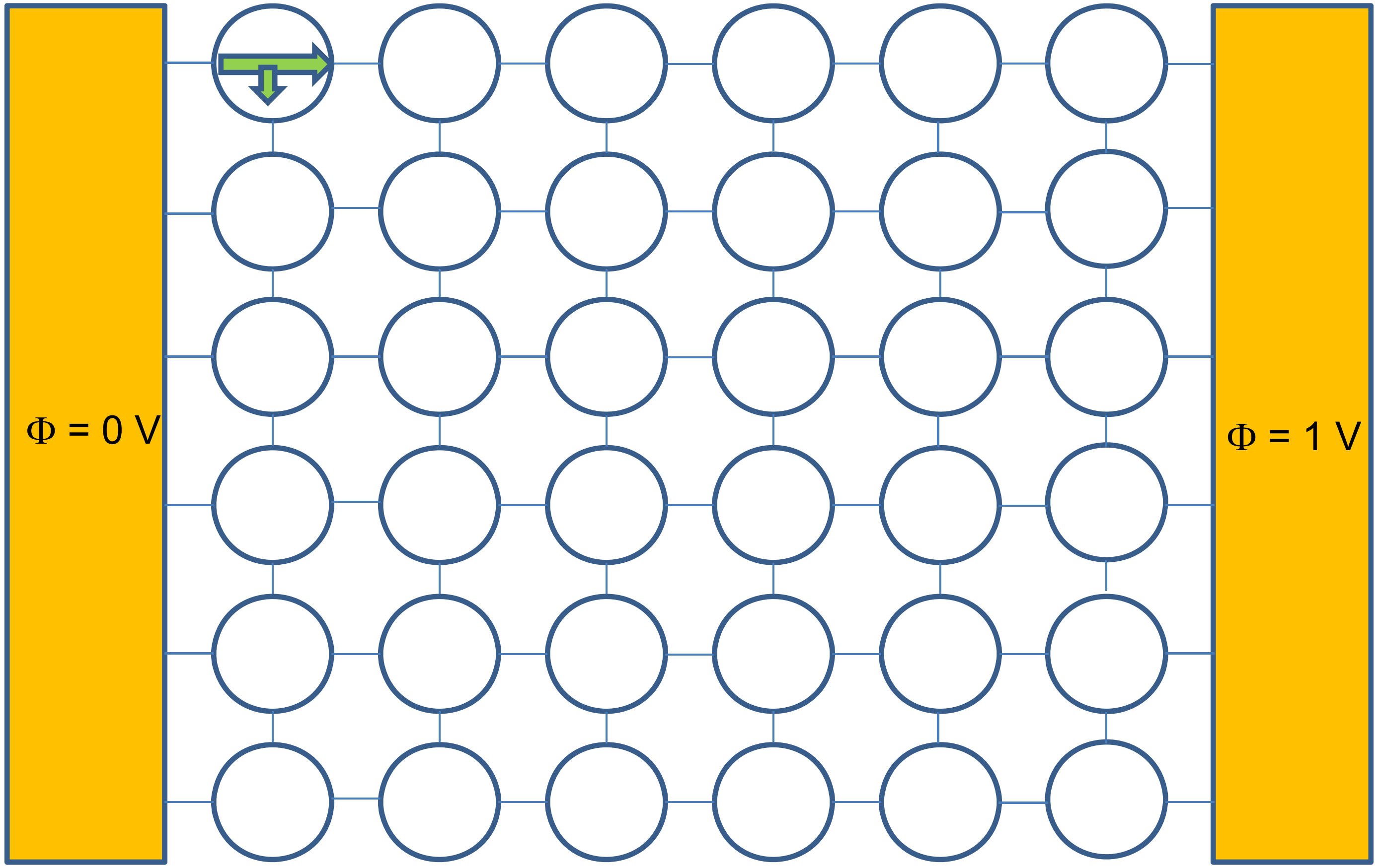



Φ = 0
V
Φ = 1
V



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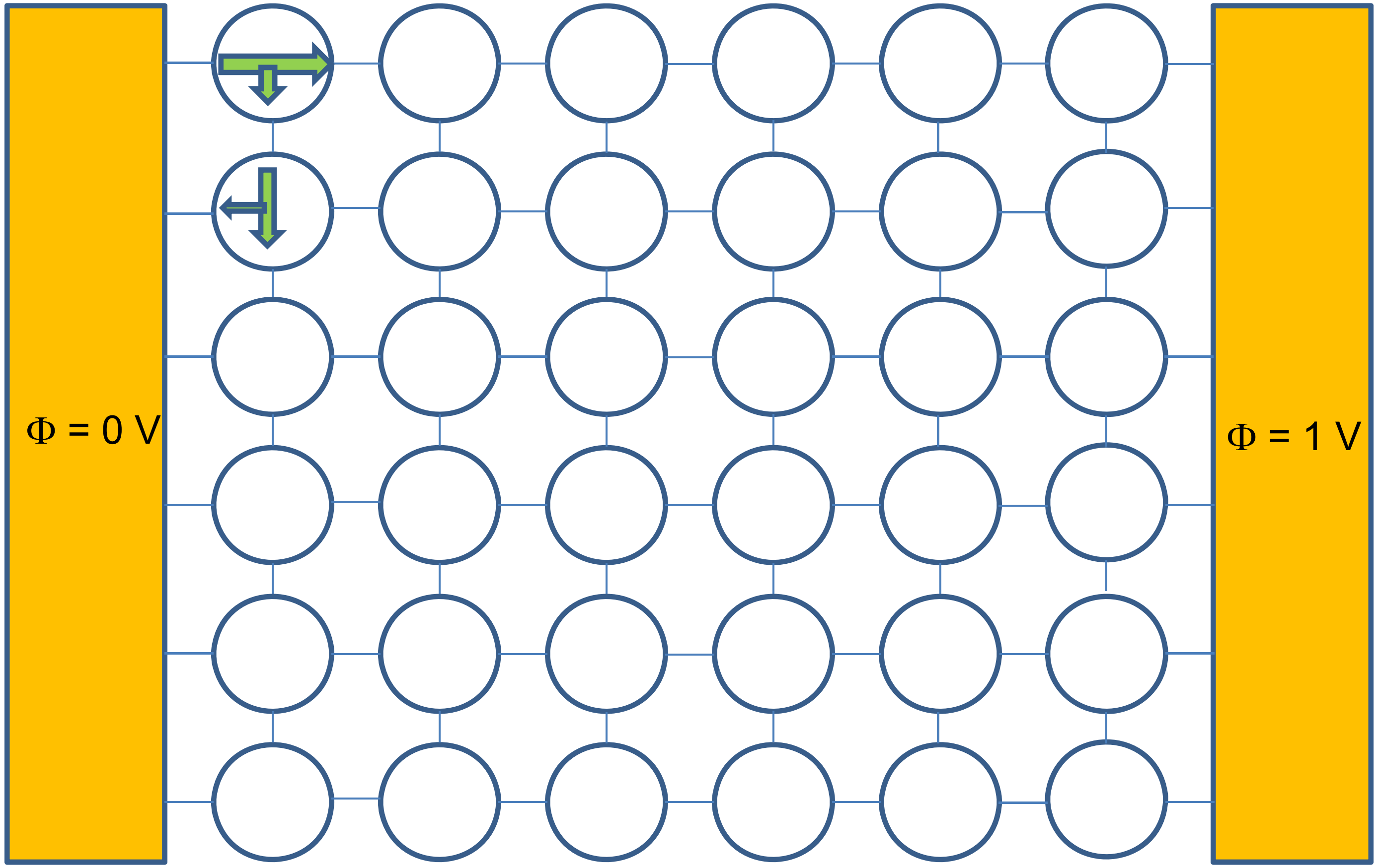
Φ = 0 V
Φ = 1 V

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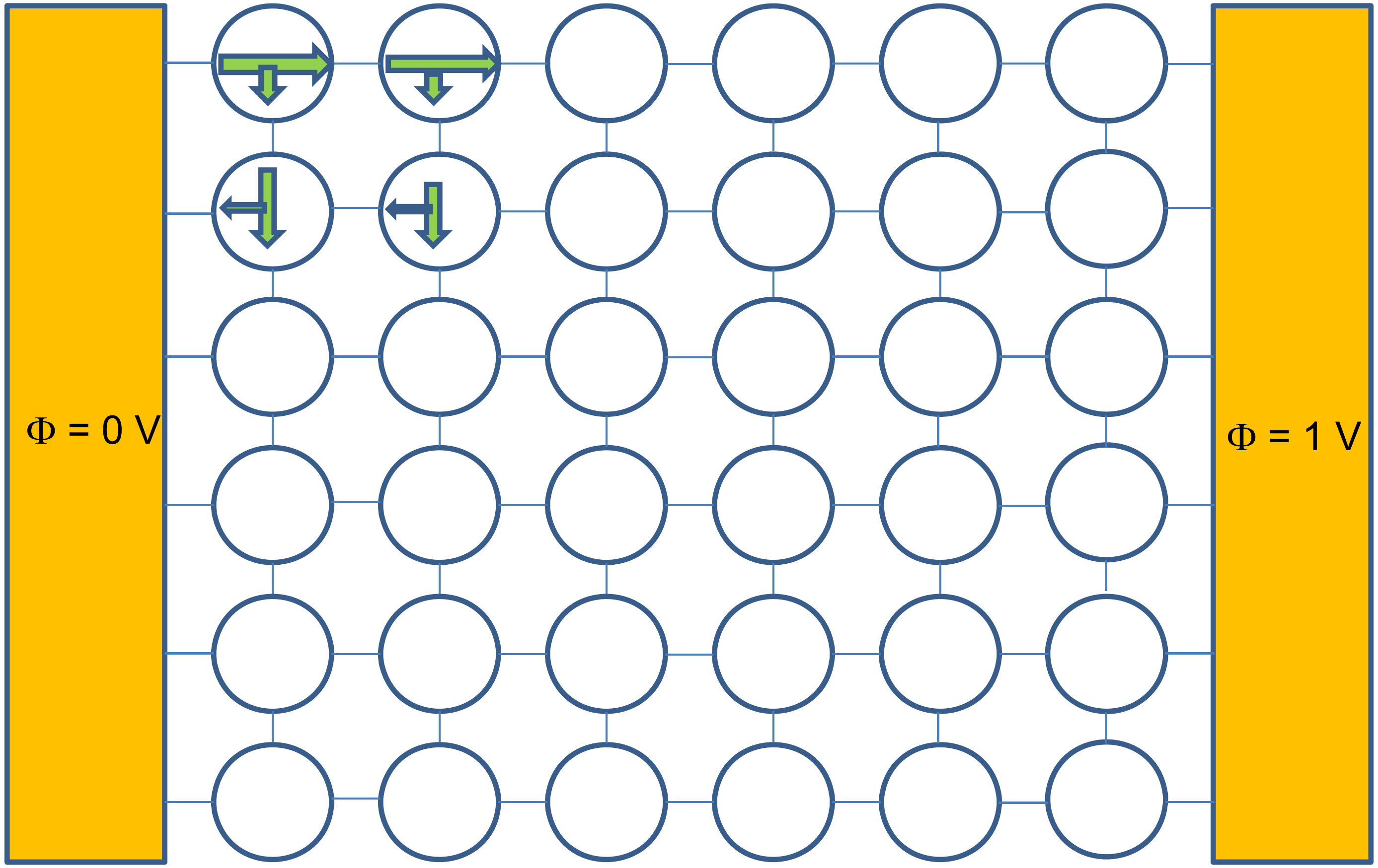
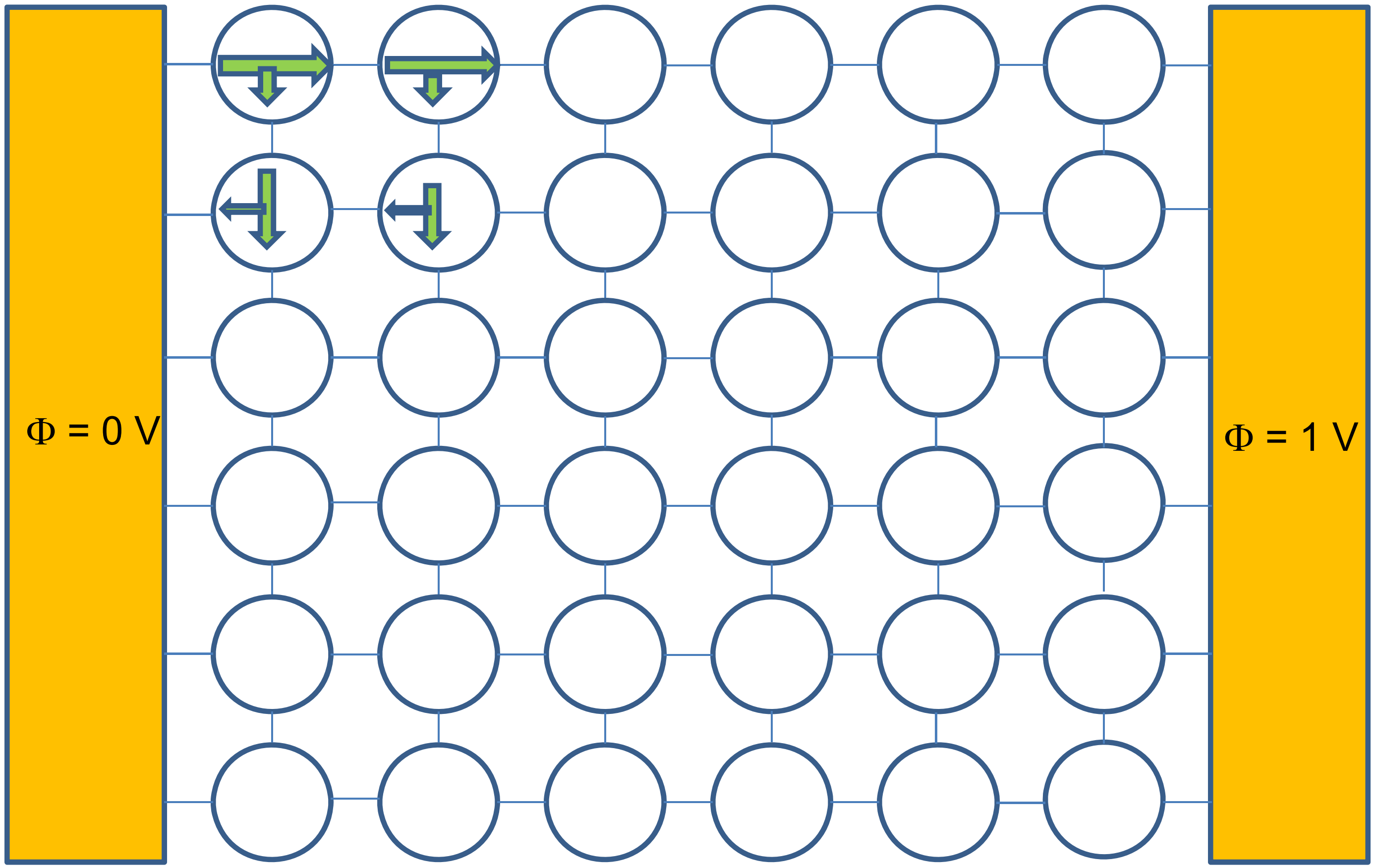
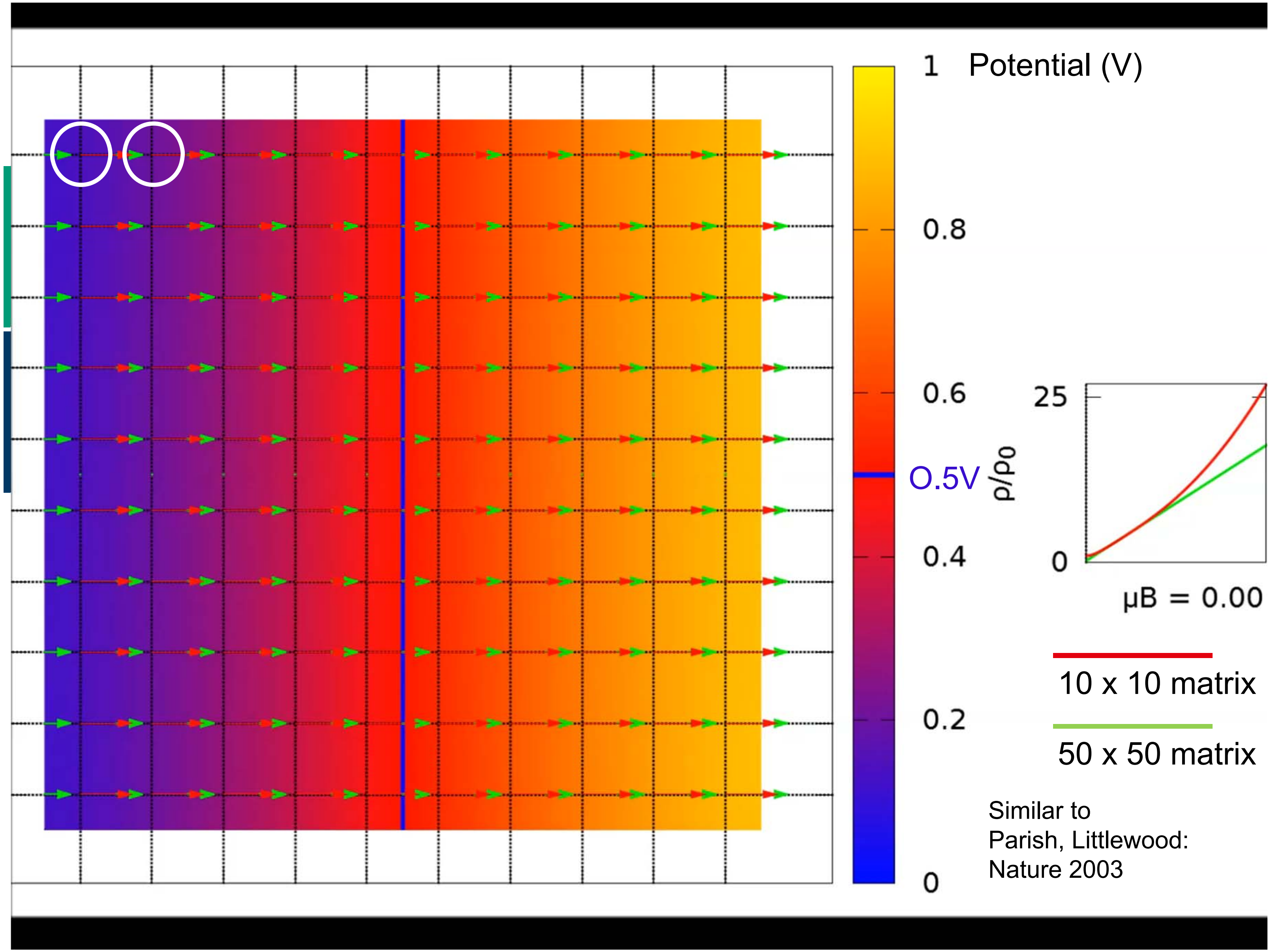


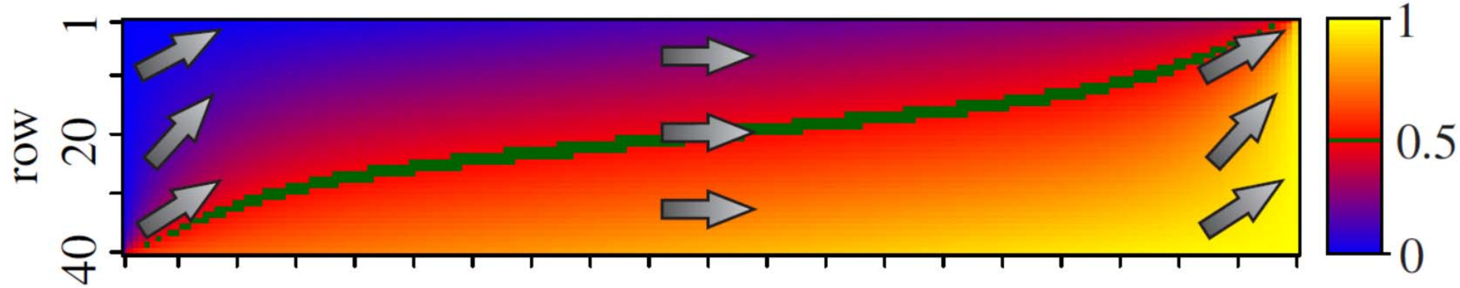


Take care for

- Kirchhoff rules (1845)
- Maxwell's equations(1864)
- Hall effect (1879)


1
Potential (V)
0.8
0.6
O.5V
0.4
0.2
0
25
ρ/ρ0
0
μB = 0.00
10 x 10 matrix
50 x 50 matrix
Similar to
Parish, Littlewood:
Nature 2003

Linear MR: a classical phenomenon



- A property of the classical resistivity tensor:
- Scaling (for $\frac{B}{ne} \gg \rho_0$)

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} \rho_0 & B/ne \\ -B/ne & \rho_0 \end{pmatrix} \cdot \begin{pmatrix} j_x \\ j_y \end{pmatrix}$$ simplifies to $$E_x = B/ne \cdot j_y$$ $$E_y = -B/ne \cdot j_x$$

→ When E-fields are (asymptotically) constant,

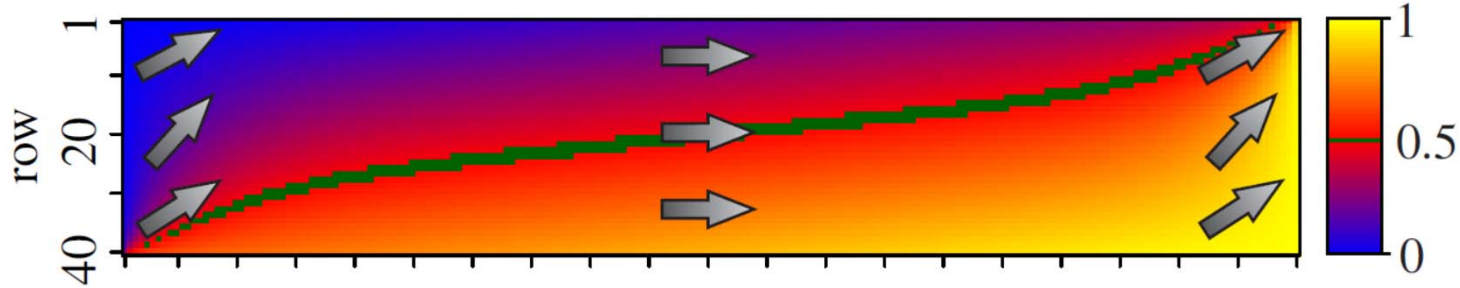
$$j * B = \text{constant} \rightarrow \rho(B) = \frac{E}{j} \propto B$$

The linear-in-B behavior is built in, however ist prefactor is most often zero.

Further Requirement: Inhomogeneity of off-diagonal term

Kisslinger, Ott, Weber: Phys. Rev. B. 95, 24204 (2017)

Linear MR: a classical phenomenon



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Kisslinger, Ott, Weber: Phys. Rev. B. 95, 24204 (2017)

Mosaic-like conductors

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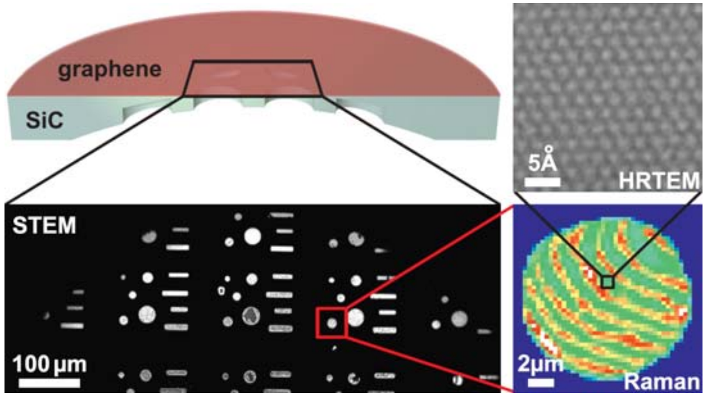


Robust membranes of bilayer graphene

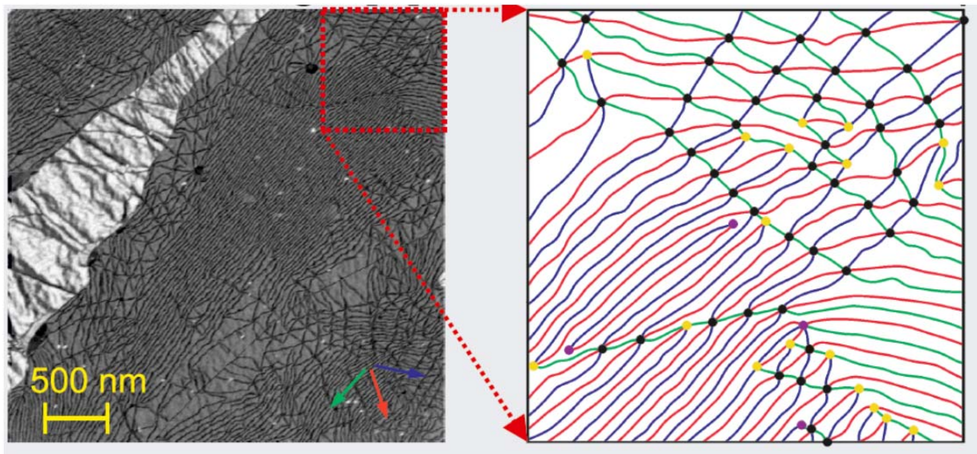
D. Waldmann,..... A. Hirsch, S. Maier, P. Schmuki, T. Seyller, E. Spiecker, H.B. Weber:

ACS nano 7, 4441 (2013)

Dislocation networks in bilayer graphene

B. Butz,…H.B. Weber, B. Meyer and E. Spiecker

Nature 505, 513 (2014)



Bilayer graphene

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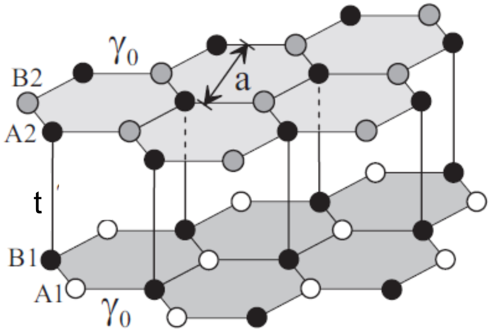
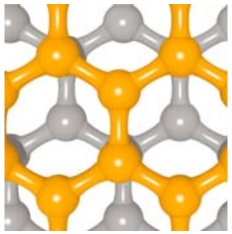
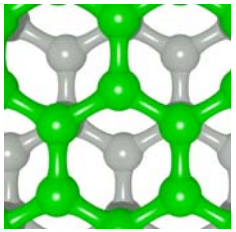
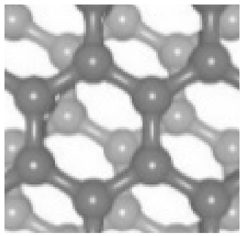




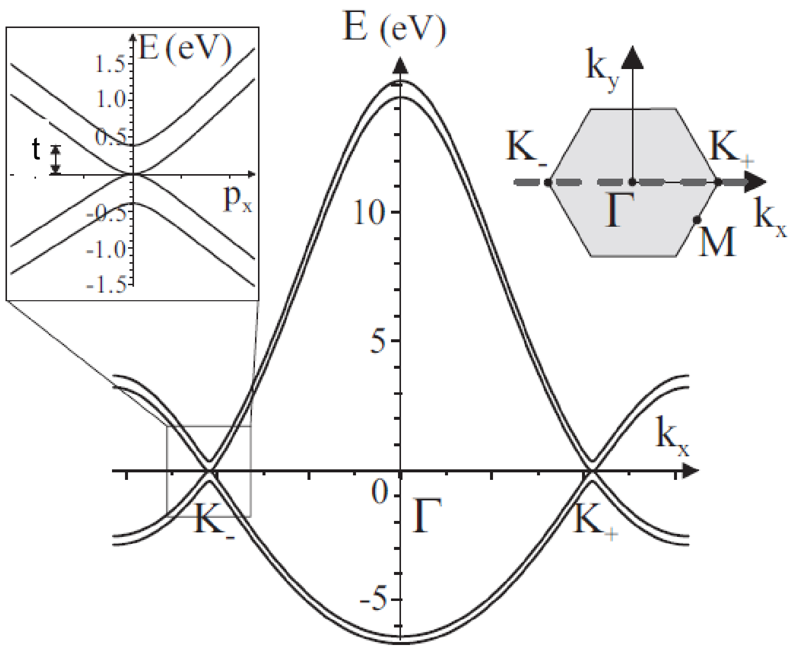
AB



AC



(in between)



Partial dislocations: what is their impact on the electronic system?

Bernal stacking

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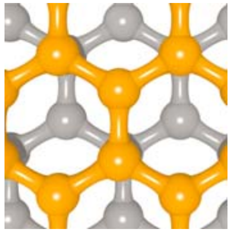
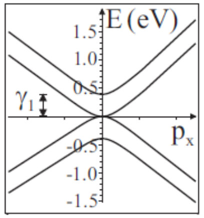
AB stacking



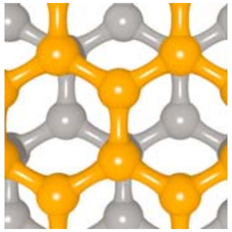


H_{AB}

$$\begin{pmatrix} 0 & \hbar v_F k e^{-i\theta_k} & t_\perp & 0 \\ \hbar v_F k e^{i\theta_k} & 0 & 0 & 0 \\ t_\perp & 0 & 0 & \hbar v_F k e^{i\theta_k} \\ 0 & 0 & \hbar v_F k e^{-i\theta_k} & 0 \end{pmatrix}$$

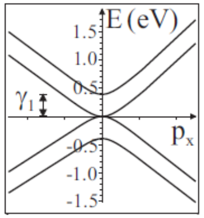
Bernal stacking

AB stacking

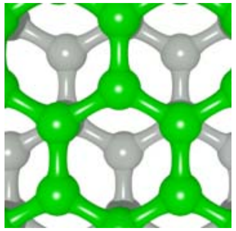


H_{AB}

$$\begin{pmatrix} 0 & \hbar v_F k e^{-i\theta_k} & t_\perp & 0 \\ \hbar v_F k e^{i\theta_k} & 0 & 0 & 0 \\ t_\perp & 0 & 0 & \hbar v_F k e^{i\theta_k} \\ 0 & 0 & \hbar v_F k e^{-i\theta_k} & 0 \end{pmatrix} \begin{pmatrix} E \\ \hbar v_F k e^{i\theta_k} \\ \sigma_1 E \\ \sigma_1 \hbar v_F k e^{-i\theta_k} \end{pmatrix} = E \begin{pmatrix} E \\ \hbar v_F k e^{i\theta_k} \\ \sigma_1 E \\ \sigma_1 \hbar v_F k e^{-i\theta_k} \end{pmatrix}$$



AC stacking



H_{AC}

$$\begin{pmatrix} 0 & \hbar v_F k e^{-i\theta_k} & 0 & 0 \\ \hbar v_F k e^{i\theta_k} & 0 & 0 & t_\perp \\ 0 & 0 & 0 & \hbar v_F k e^{i\theta_k} \\ 0 & t_\perp & \hbar v_F k e^{-i\theta_k} & 0 \end{pmatrix} \begin{pmatrix} \hbar v_F k e^{-i\theta_k} \\ E \\ \sigma_1 \hbar v_F k e^{+i\theta_k} \\ \sigma_1 E \end{pmatrix} = E \begin{pmatrix} \hbar v_F k e^{-i\theta_k} \\ E \\ \sigma_1 \hbar v_F k e^{+i\theta_k} \\ \sigma_1 E \end{pmatrix}$$

Eigenvalues (energies) are identical, but eigenfunctions are not!

At $E = 0$, they are even orthogonal!

Electrons can not cross the partial dislocation

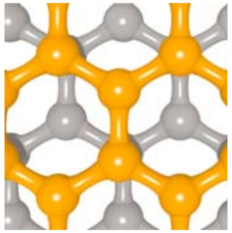
Bilayer graphene as mosaic-like conductor

This leads to a distorted quantum mechanical wave pattern:

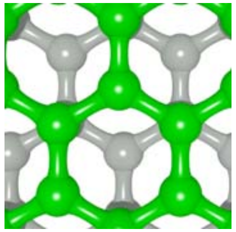
Mosaic-like conductor

Current pathways distorted:

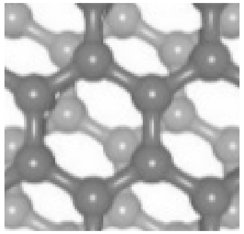
Linear Magnetoresistance



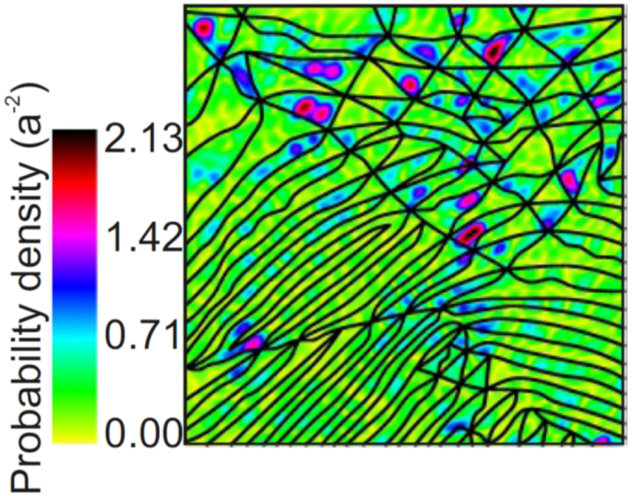
AB



AC



partial dislocation



S. Shallcross, S. Sharma and H.B. Weber,
Nature communications 8, 342 (2017)
F. Kisslinger, …E. Spiecker, S. Shallcross, H.B. Weber,
Nature physics **11**, 650 (2015)
F. Kisslinger, .. H.B. Weber, Annalen der Physik (2017)

Simple questions

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Question:
Can we drive a current in a metal with light fields?

Light fields penetrating graphene

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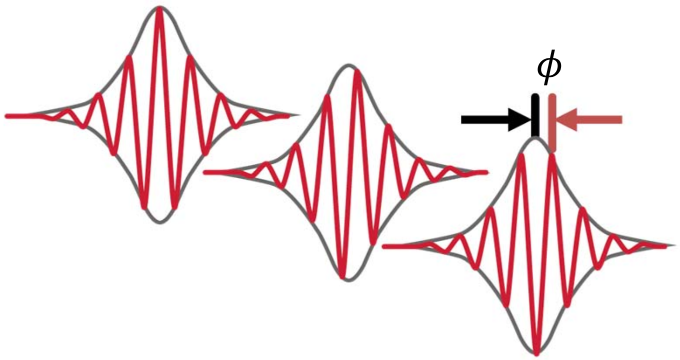
Peter Hommelhoff (FAU): waveform control via carrier envelope phase

Electric field of ultrashort light pulses:

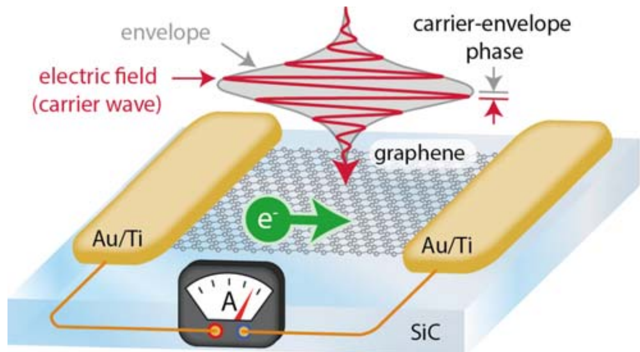


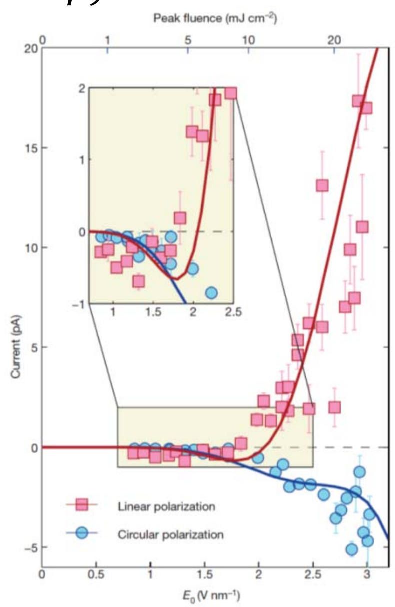
envelope carrier

$$E(t) = f(t)\cos(\omega t)$$

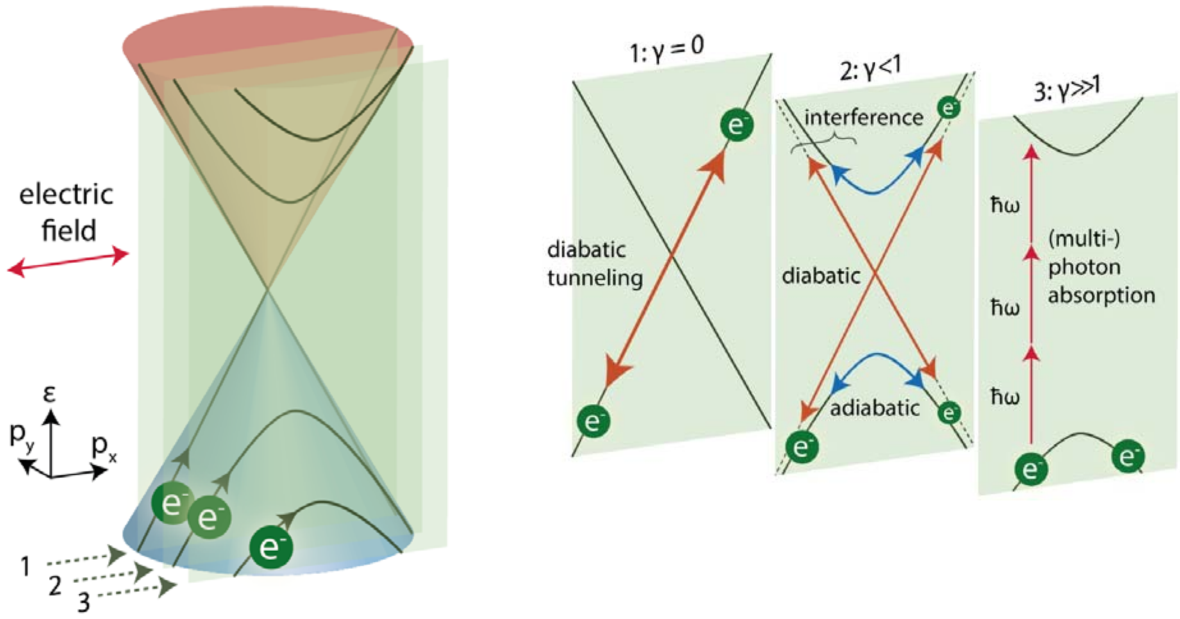
Carrier-envelope-phase

$$E(T) = f(t)\cos(\omega t + \phi)$$

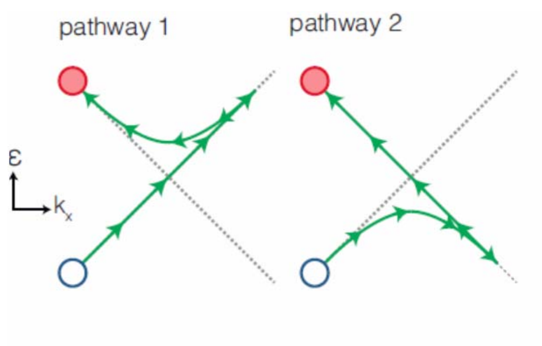




Light fields penetrating graphene



Landau-Zener-Stückelberg processes:



Light fields penetrating graphene

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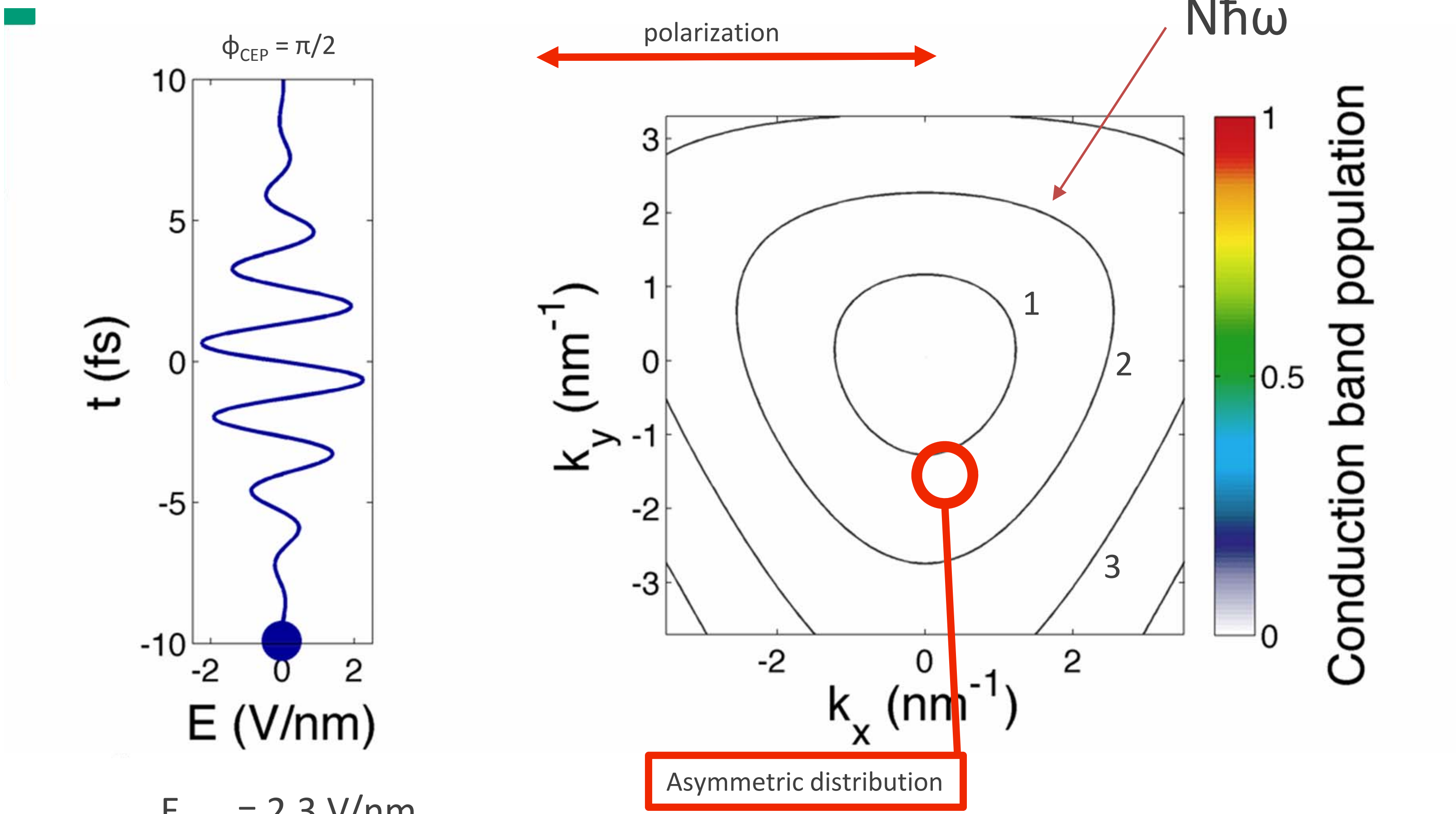
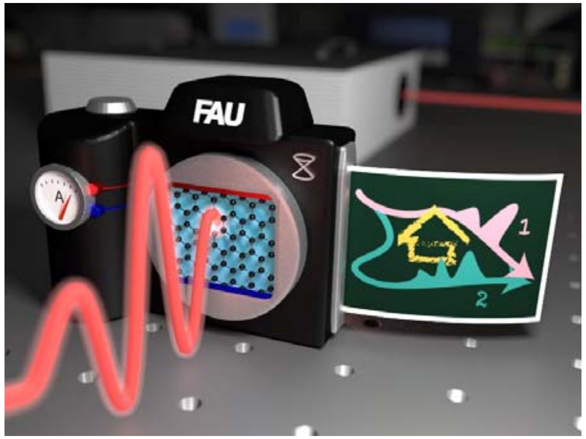
Tight binding calculation of semiclassical electron motion



E_{amp} = 2.3 V/nm

Light fields penetrating graphene

Press release:
The fastest light-driven current source



T. Higuchi, C. Heide, K. Ullmann, H. B. Weber, P. Hommelhoff
Nature 550, 224 (2017)

C. Heide, T. Higuchi, H.B. Weber, P. Hommelhoff
Phys. Rev. Lett. 121, 207401 (2018)

Simple questions

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Question:
Why is light emitted when electrons tunnel from a metal to a metal?

Light emission from tunneling

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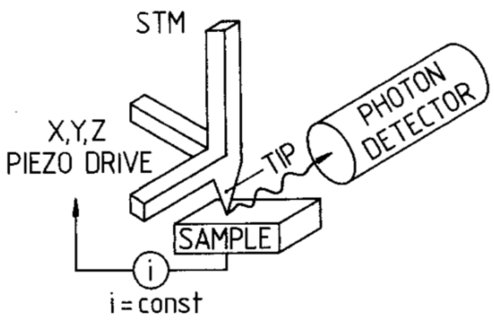
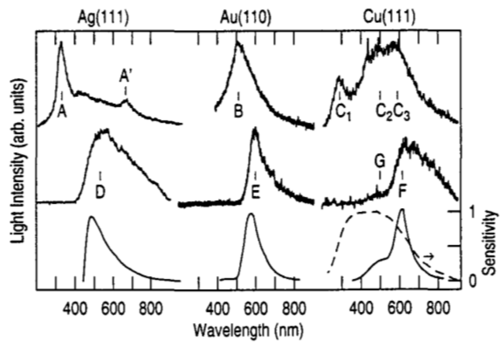
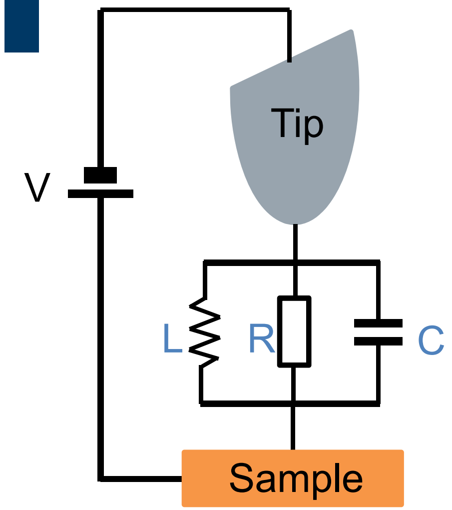
Very old days of STM: Gimzewski 1988



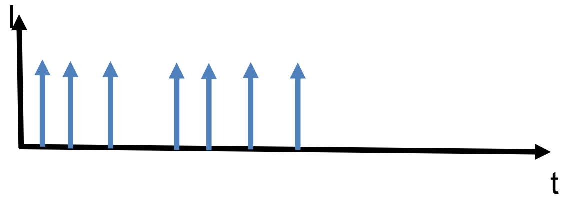




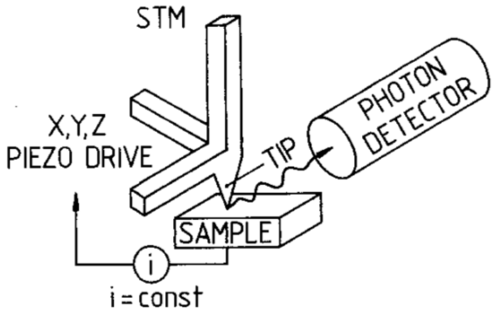
Common understanding:

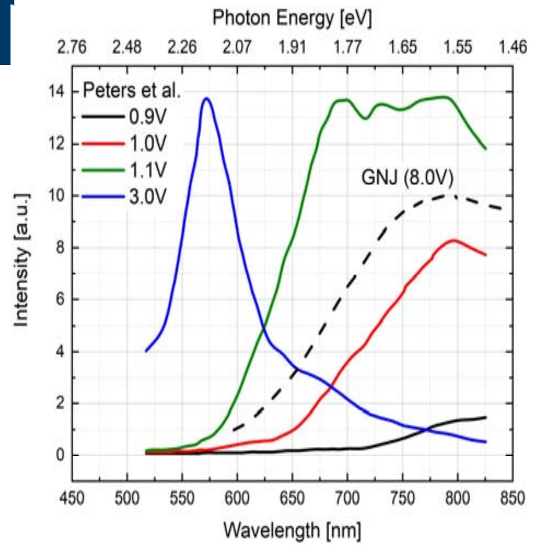
The granular nature of current excites electromagnetic resonances (plasmons), which decay as photons

Electromagnetic generation of light!



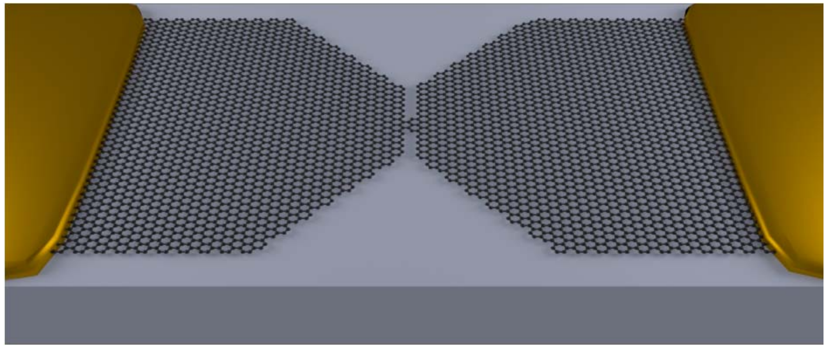
Light emission from tunneling





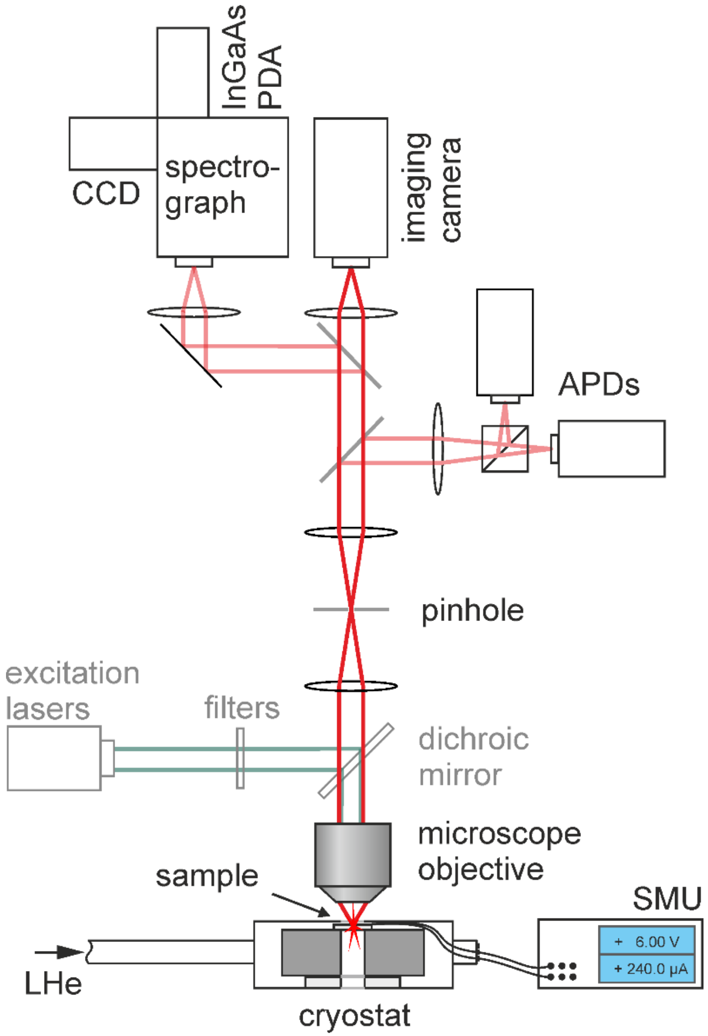
STM at Ag surface, Peters et al., PRL (2017)

New experiment:
Graphene nanojunctions (GNJ)



- Flat geometry
- Transparent, spectrally flat
- Extremely stable
- No plasmonic contributions (in the visible)

Confocal microscope



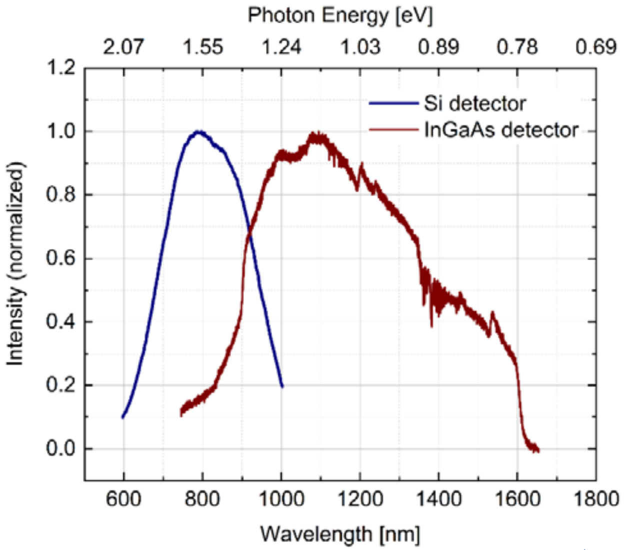
- Custom confocal fluorescence microscope setup
  - Imaging
  - Spectroscopy
  - Photon statistics

- Spectral range (spectroscopy): 400 nm – 1600 nm
- Temperature range: 3.5 K – 300 K

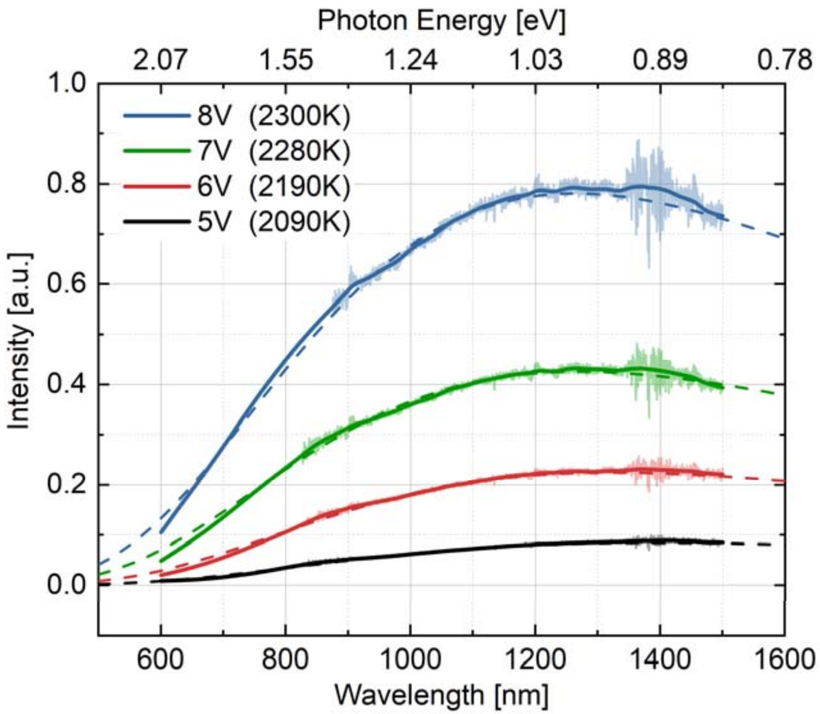
- Optical excitation
- Electrical excitation

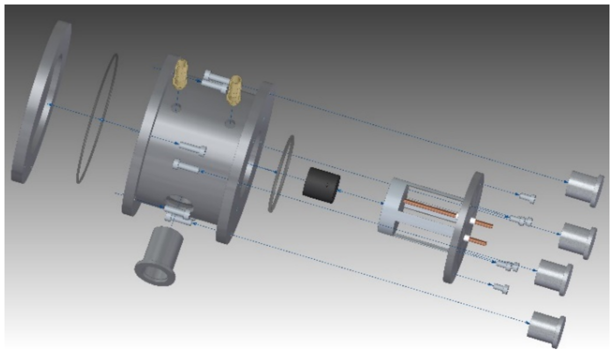
Special thanks to
Prof. Stephan Götzinger (FAU)

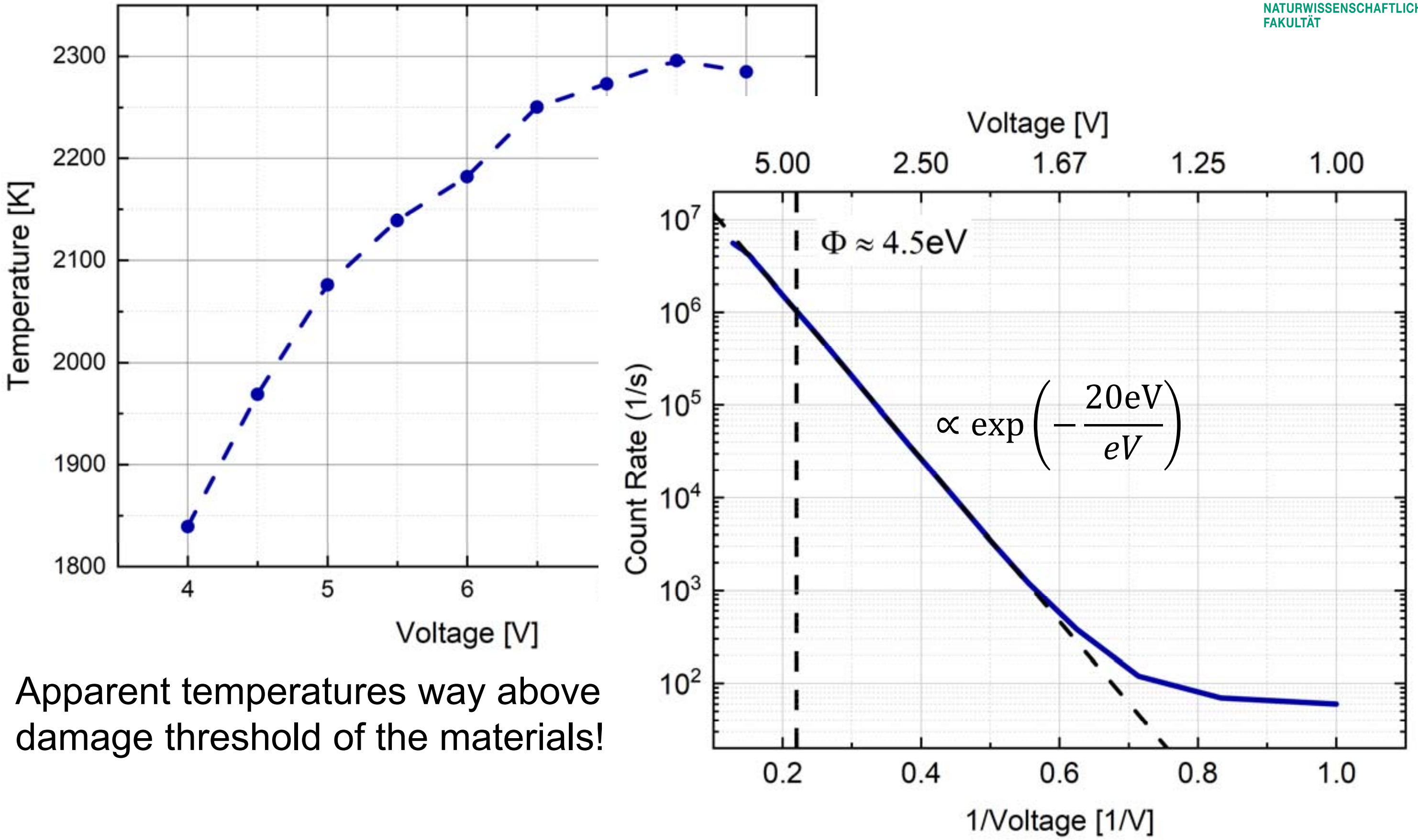
Blackbody Spectra



Calibration





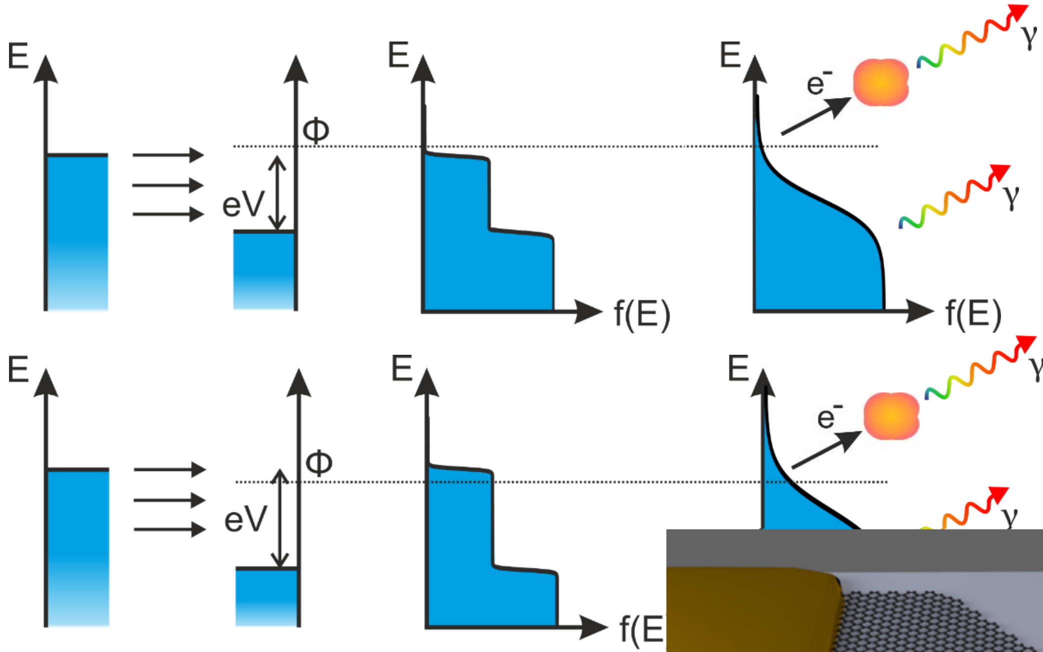


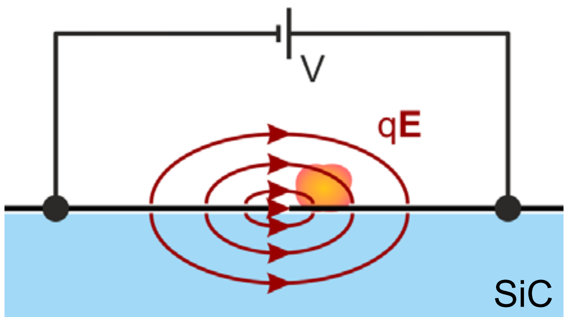
Apparent temperatures way above damage threshold of the materials!

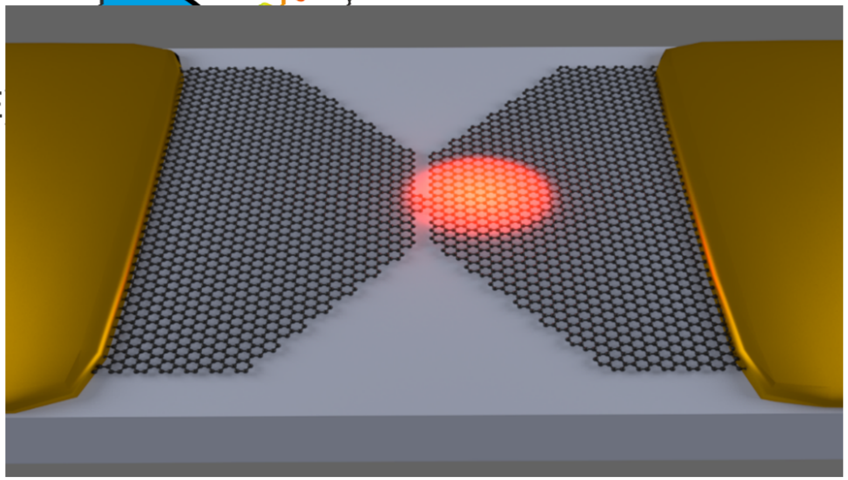
Exponential law over 4 decades

Insensitive to work function Φ

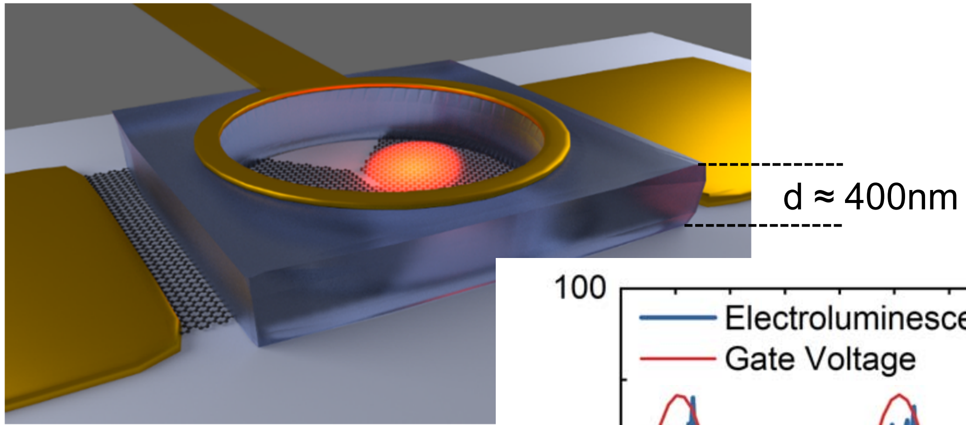
Thermionic electron emission

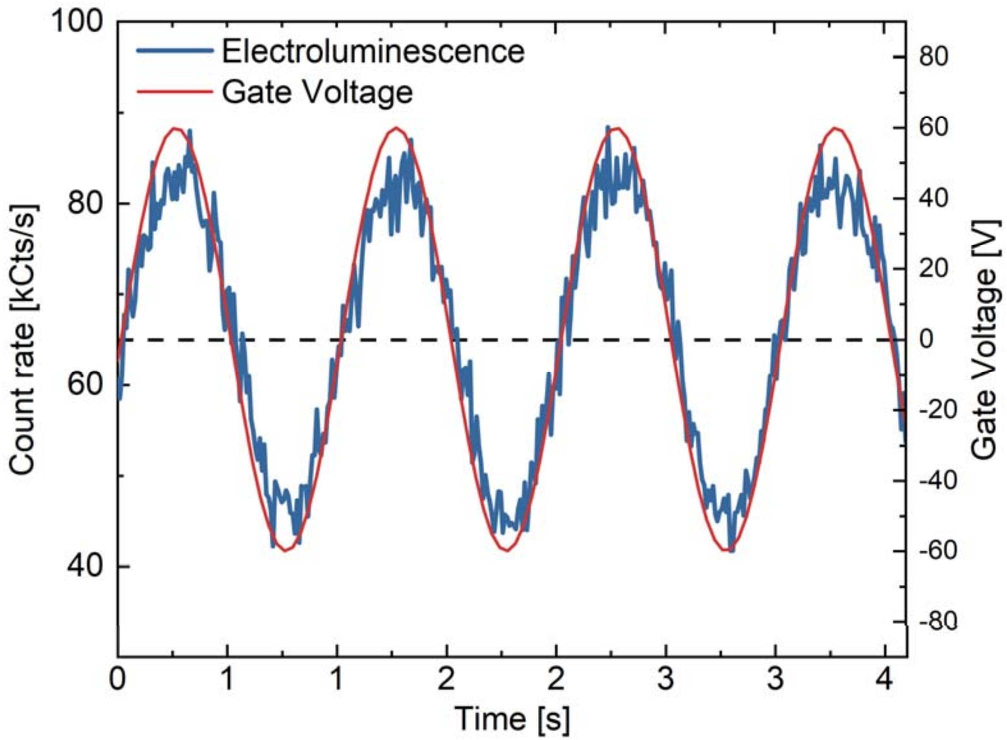






Electron cloud





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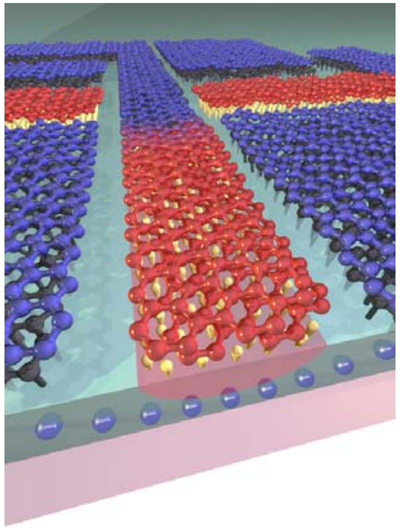
Epitaxial graphene on SiC

Physics in the graphene plane

The graphene/SiC system: a Schottky junction

Physics in SiC: Colour centres



Monolithic electronics

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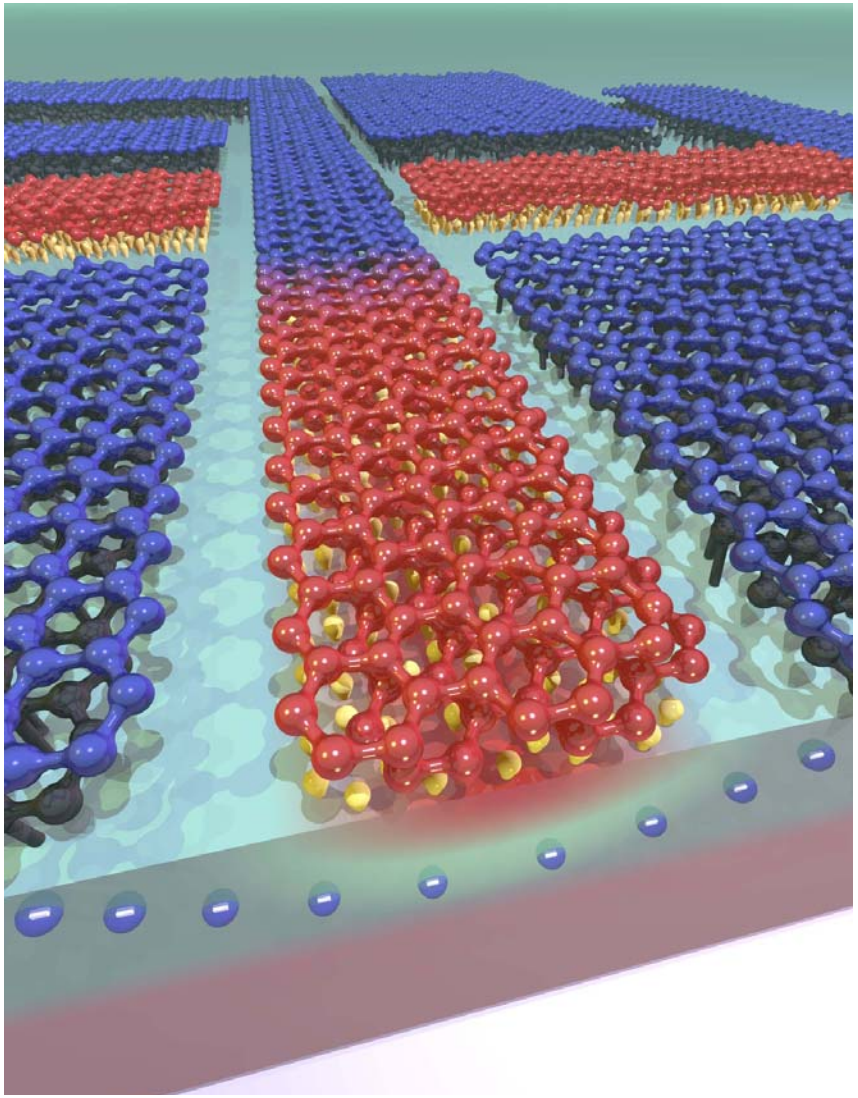

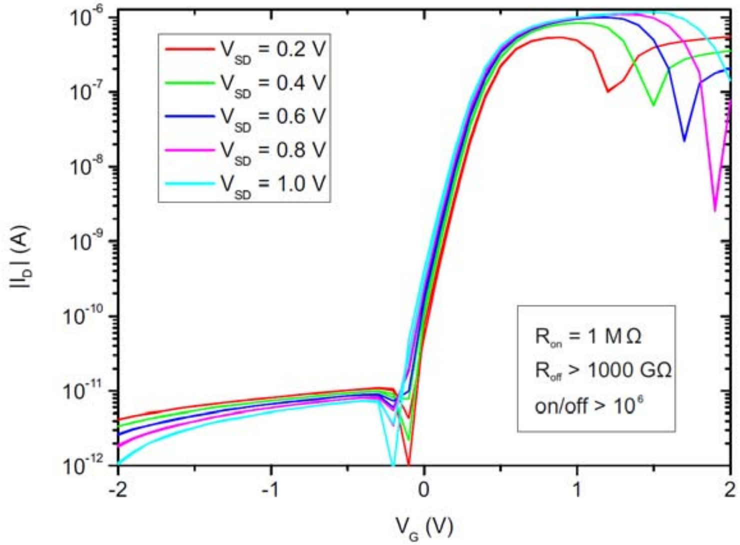

Graphene as metal,

SiC as semiconductor

Nature materials 10, 357 (2011)

Nature communications 3:957 (2012)

2 patents

Simple Questions

Question:
How fast can a Schottky Diode respond?

THz response

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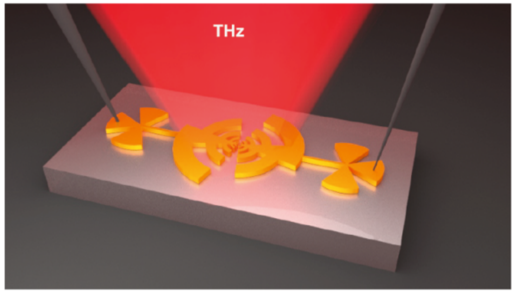

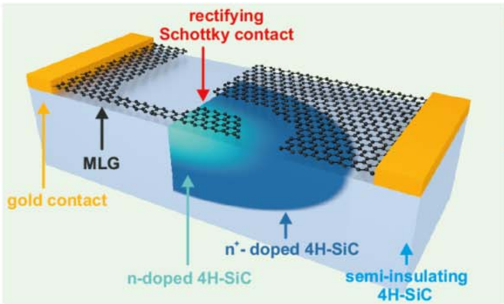

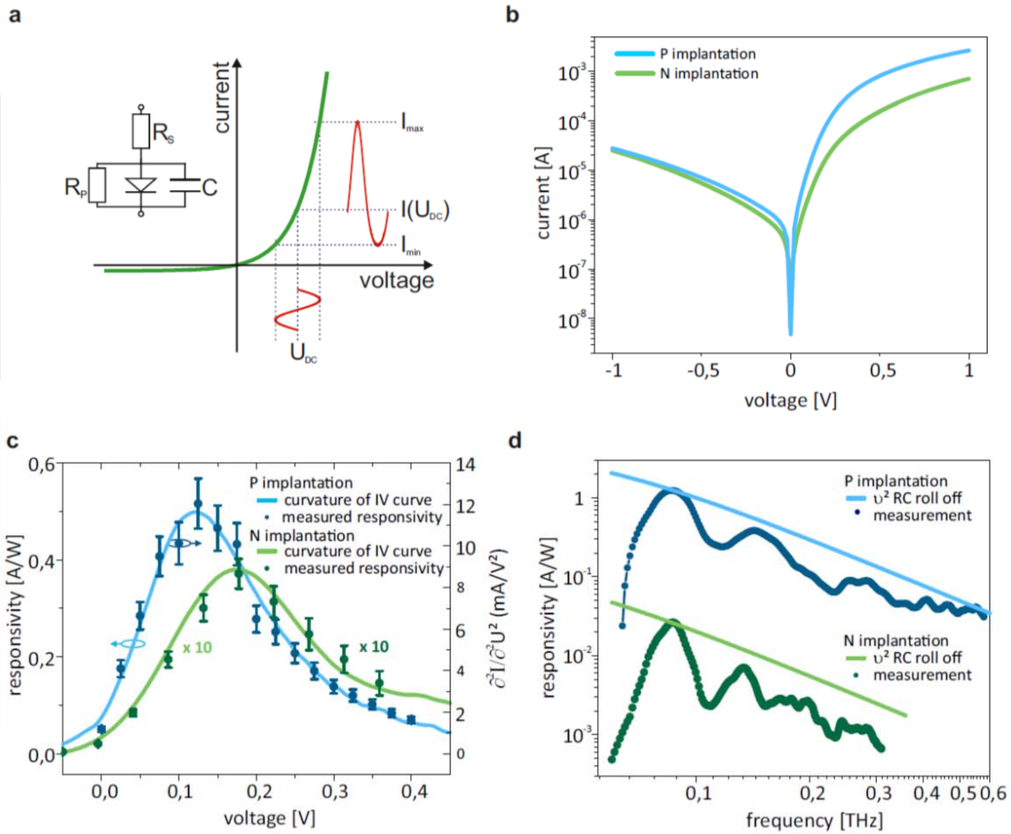

Excellent responsivity (1.1 A/W @ 90 GHz)

One-by-one correspondence between minute and picosecond timescales

Ultrafast response

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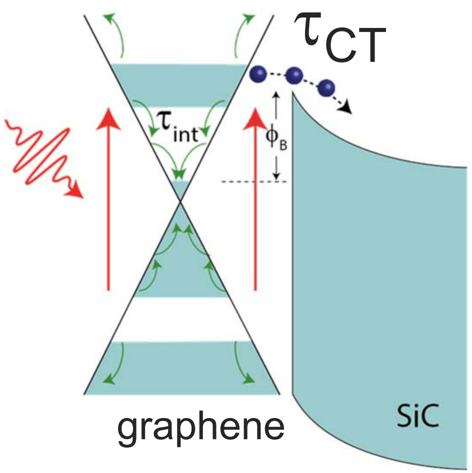
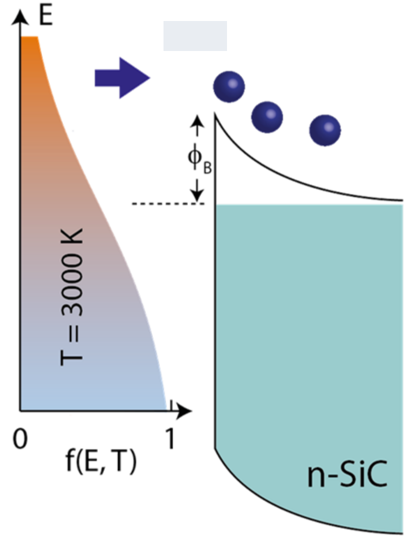


rapid thermalization



Prompt internal photoemission (**PIPE**)

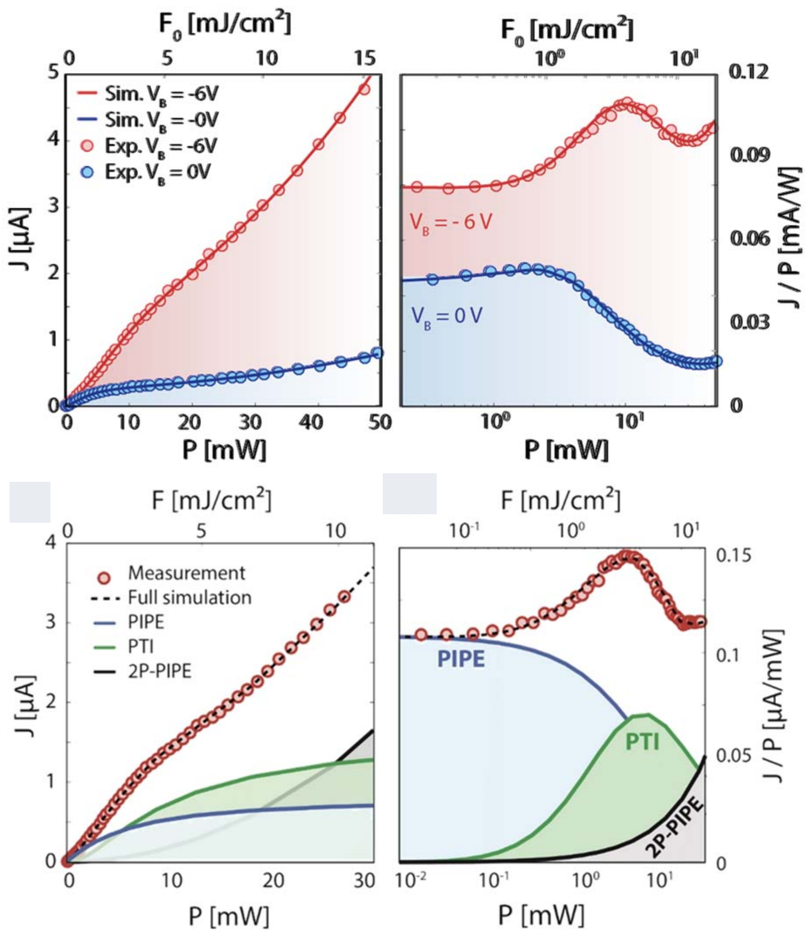
Saturable absorption

- competition between pulse duration τ_p and internal time scale τ_{int} ~ 20 -50 fs
- additional decay channel: charge transfer with τ_{CT}

Photo-thermionic emission (**PTI**)
(note: PTE = photo-thermo-electric)

With P. Hommelhoff

Schottky diode as photodetector



Increase of bias voltage

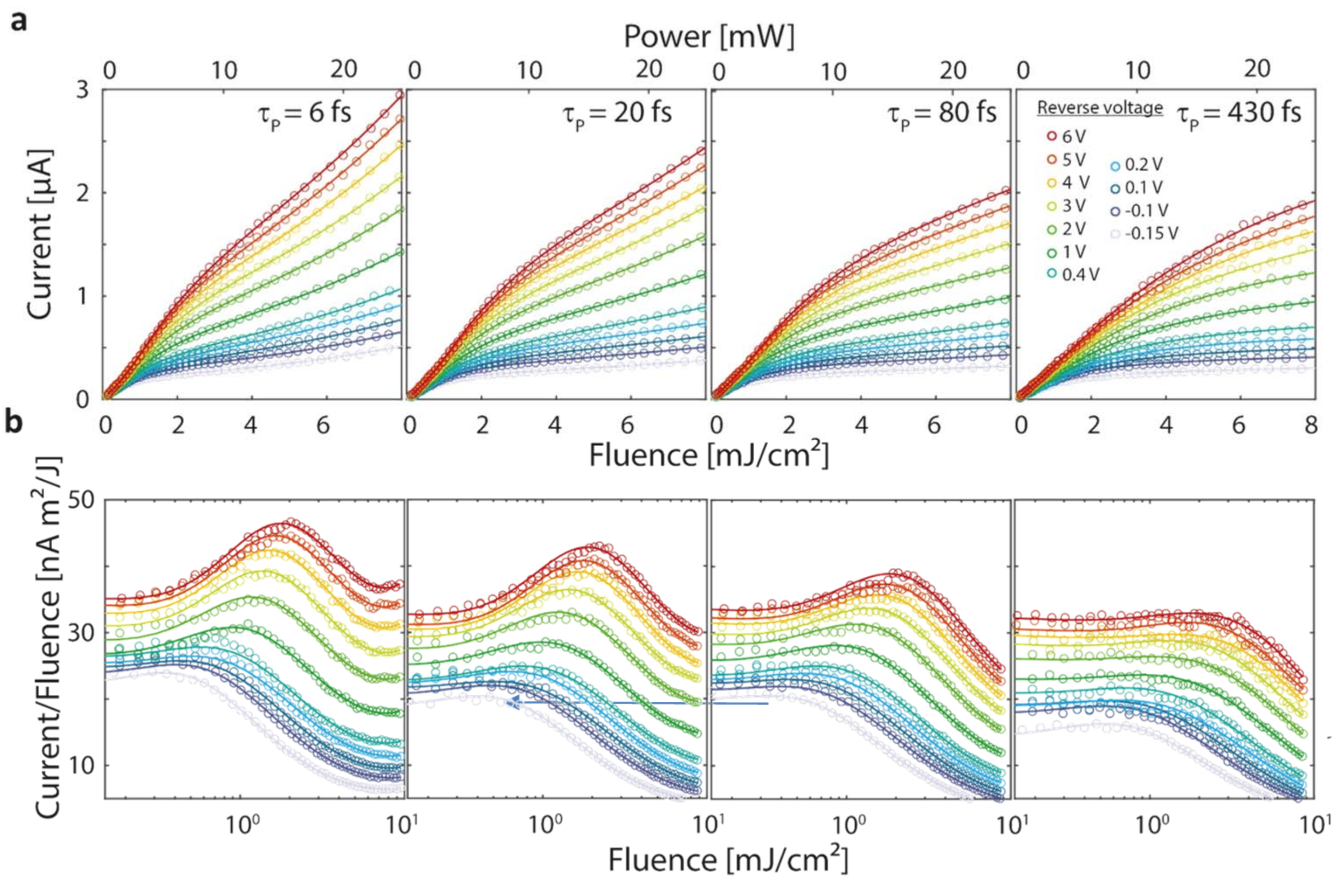
- barrier becomes thinner
- increase of IQE
- saturation shifts to larger P
- PTI more dominant at highe laser power

Numerical simulation based on

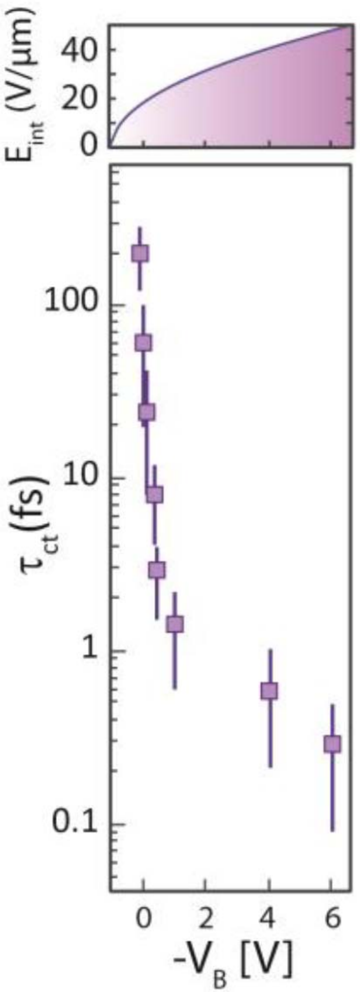
- rate equations and
- two-temperature model

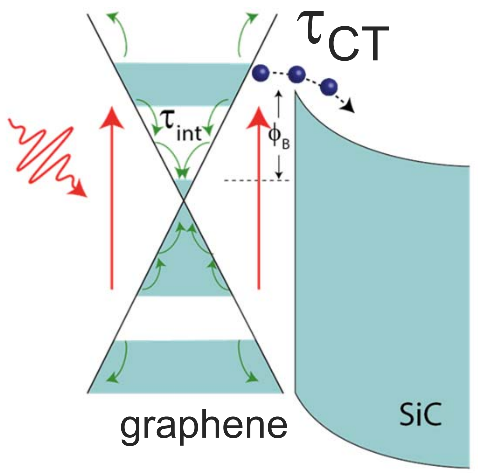
Simulation can explain experimental data over entire range explored

Systematic dataset



Extraction of timescales





Fastest timescale extracted:
τ_{ct} = 280 attoseconds!

Generation of THz radiation

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Epitaxial graphene on SiC

Physics in the graphene plane

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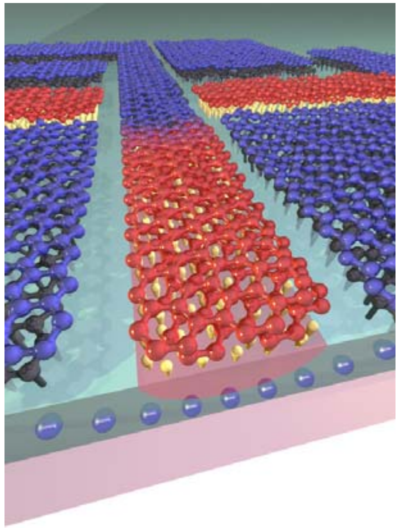
Physics in SiC: Colour centres



Our approach to color centres

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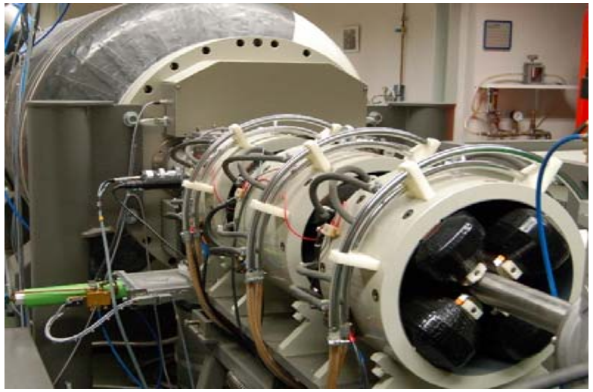
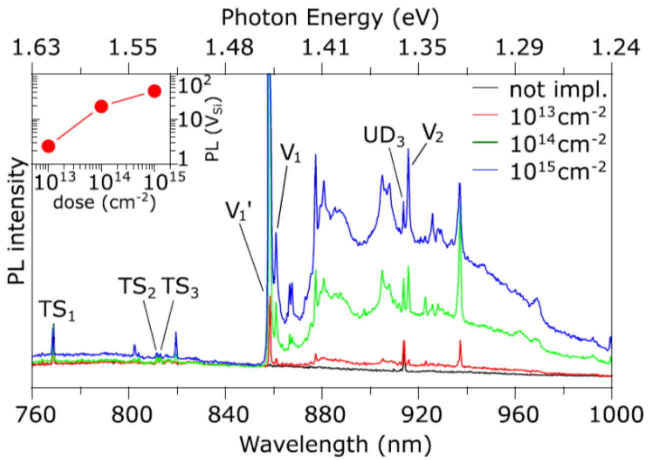
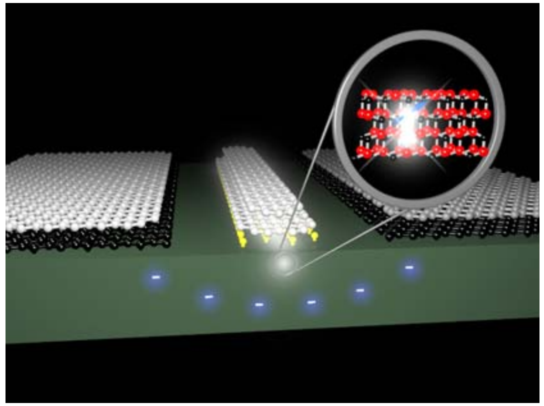
In-house creation of defects in SiC:

Ion implantation





Graphene windows as electrical interfaces



„Our own“ defects: TS with unusual properties

APL 113, 112102 (2018)

Simple questions

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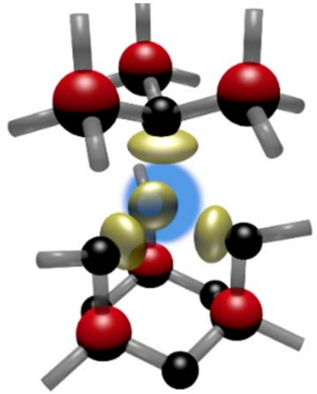
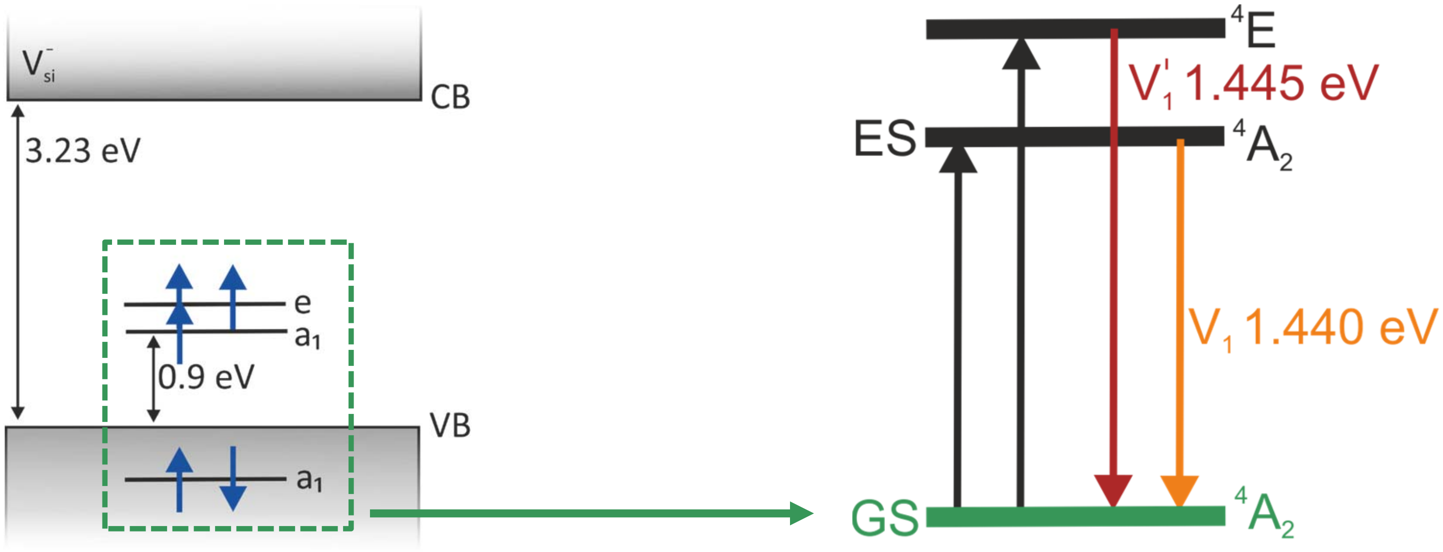
Question:
Can we control the electrostatic environment of a color center?

The silicon vacancy V_{Si} in SiC

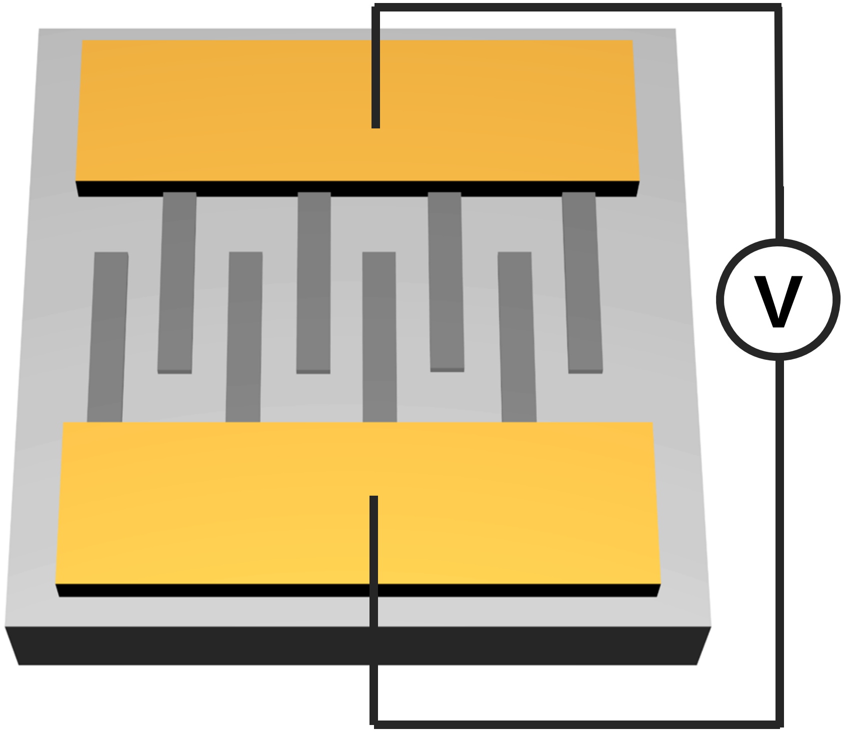
- V_{si} at cubic lattice site: C_{3V} symmetry
- 4 dangling bonds form energy levels: 2 a_1-levels and 1 e-level

→ Ground state (GS) $^4\mathrm{A}_2$ with high spin of $S = 3/2$





Graphene finger structure



- SiC with V_{Si}
- Graphene fingers:

  transparent semi-metal

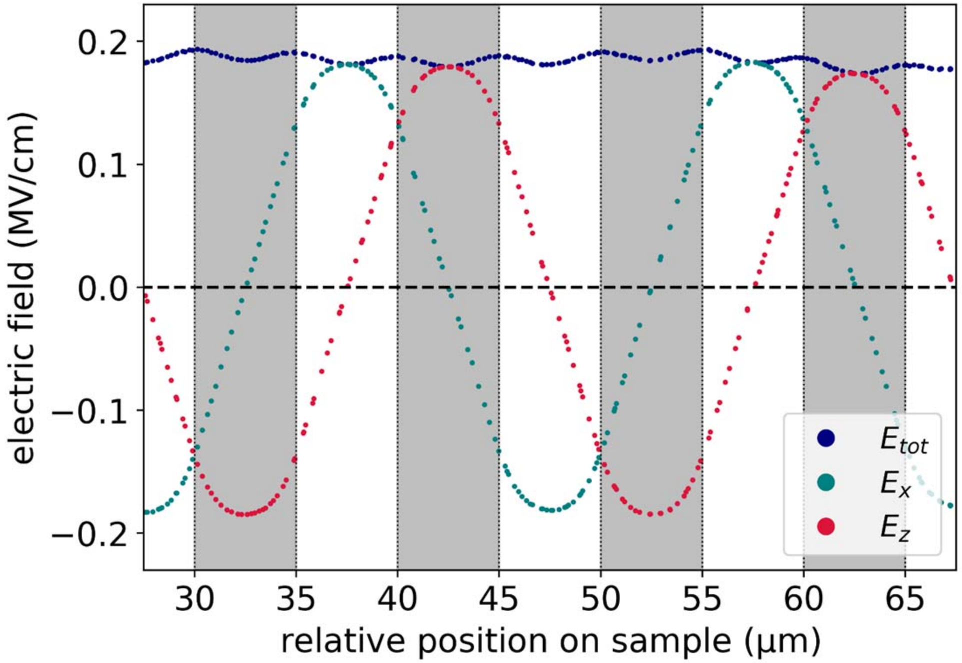
- Gold contacts

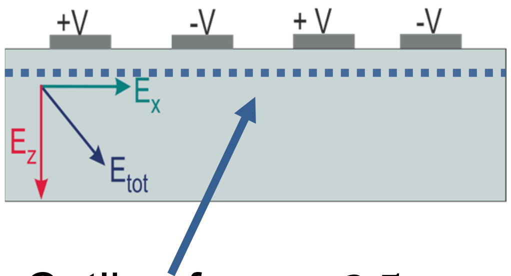
→ Investigation of PL **between and below fingers**

Comsol simulation for $240\ \mathrm{V}$

- $E_z \approx 0$
- $E_x\ max$

- $E_z\ max$
- $E_x \approx 0$

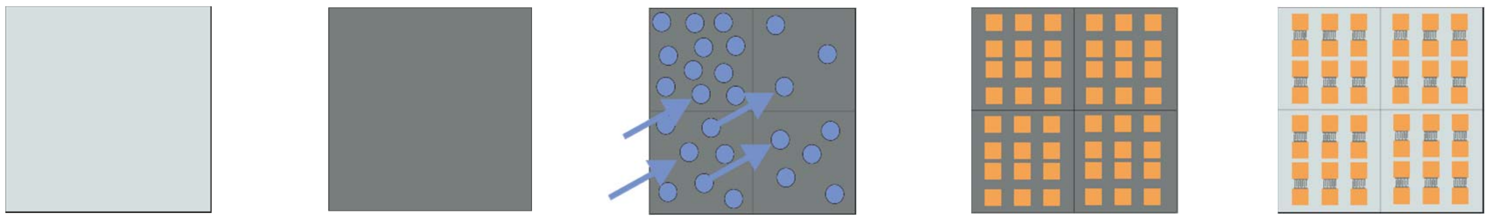




Cutline for $z = 2.5\ \mu\mathrm{m}$

Sample Preparation

High purity semi insulating 4H-SiC (HPSI) → Graphene growth → Ion implantation (H^+) → Gold contacts → Finger etching

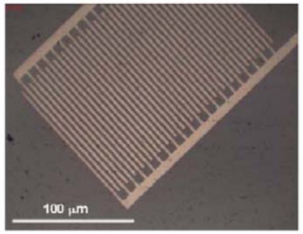


Four sectors with

different densities

Motivation

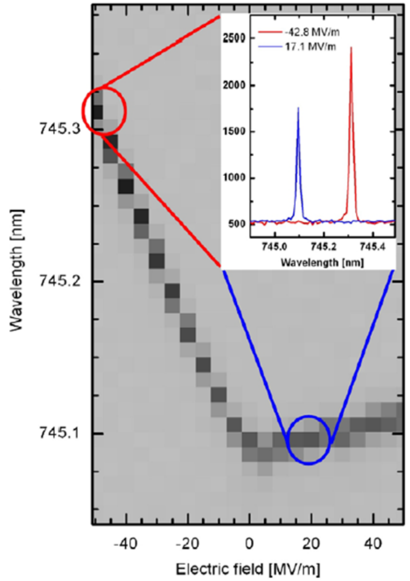
Wide-range Electrical tunability of single-photon emission from chromium based color centers in diamond
T Müller et al 2011 New J. Phys. 13075001



also fingerstructures, but in gold

What about the V_{Si}?

Shift of the PL peak



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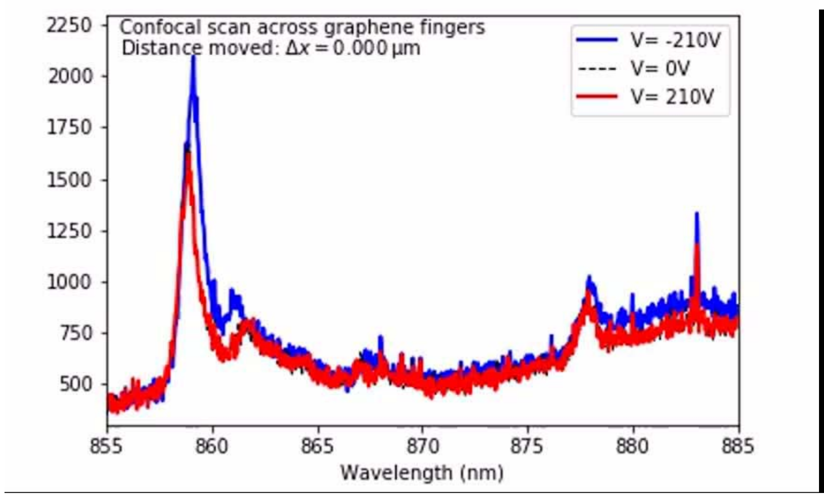
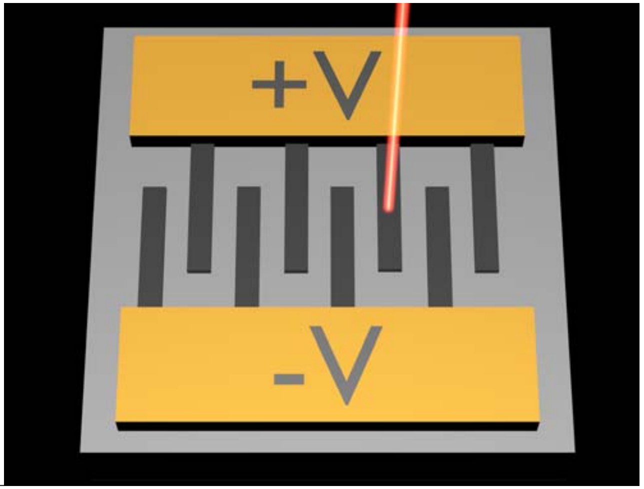
Confocal scan with applied electric field

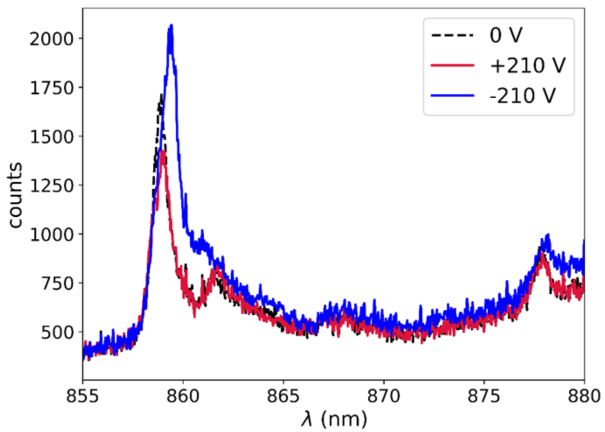




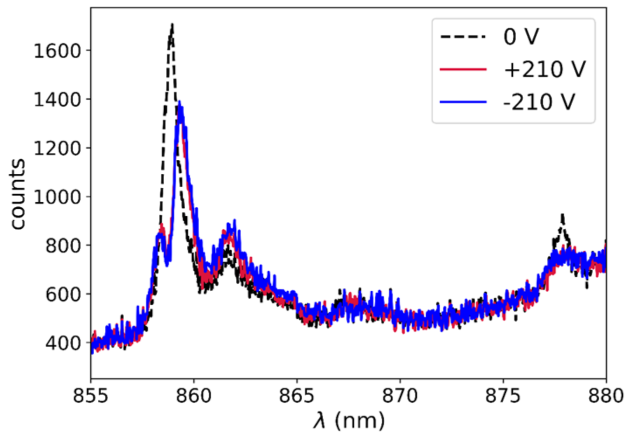
Confocal measurement with applied electric field

2 qualitatively different regions

below finger



between fingers



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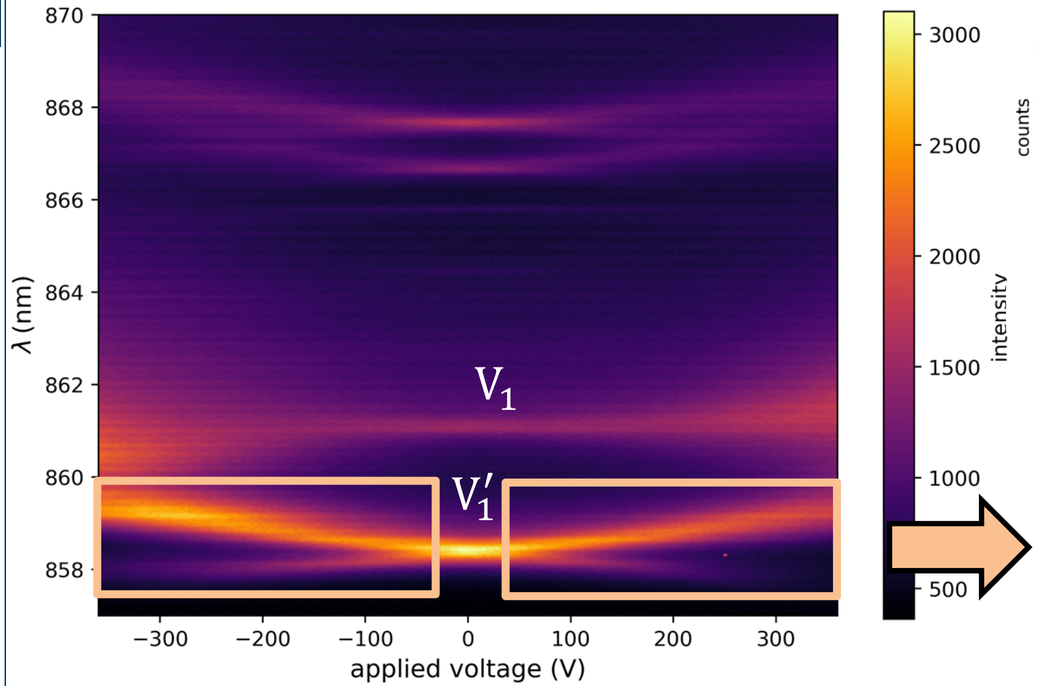
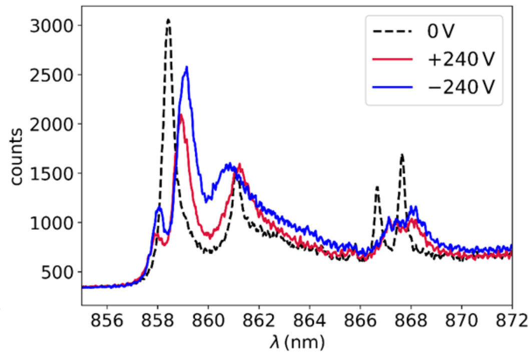
Measurement between fingers

Between fingers: Voltage sweep





V_1' splits from about 50 V on

Between fingers: Stark effect

General principal of the Stark effect:

External electric field → Shifting and splitting of spectral lines

- Interaction with electric field: $\boldsymbol{H}_{tot} = \boldsymbol{H}_0 + \boldsymbol{V}_{int}$ with $\boldsymbol{V}_{int} = -\boldsymbol{E} \cdot \boldsymbol{\mu}$

  ($\boldsymbol{\mu}$: dipole moment)

- 1. order Stark effect (**Linear Stark effect**): splitting or shift

$$U_{dip}^{(1)} = -\boldsymbol{E} \cdot \boldsymbol{\mu}$$

- 2. order Stark effect: dipole is induced $\boldsymbol{\mu}_{ind} \propto \boldsymbol{E}$

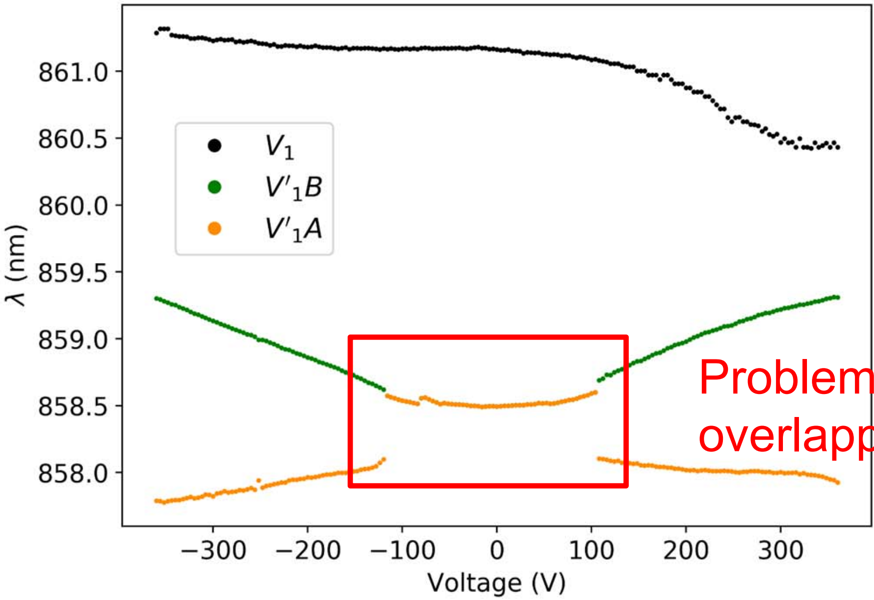
$$U_{dip}^{(2)} = -\frac{1}{2}\,\alpha\,\boldsymbol{E}^2$$

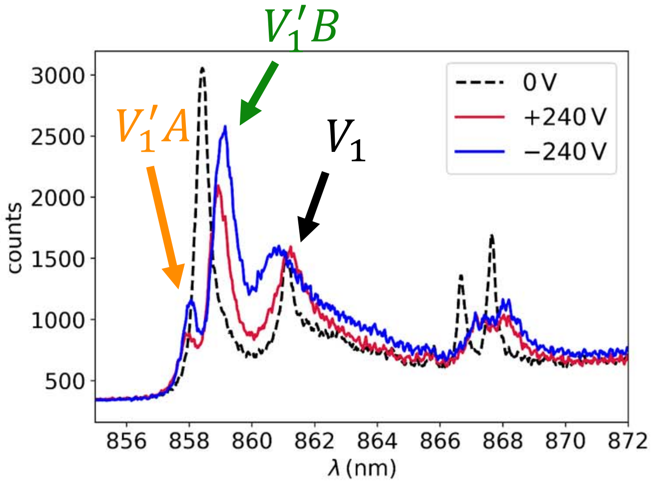
(α: polarizability)

Between fingers: Stark effect

Fit of 3 Gaussian peaks ($V_1, V_1'A$ & $V_1'B$)

→ Peak position as a function of voltage



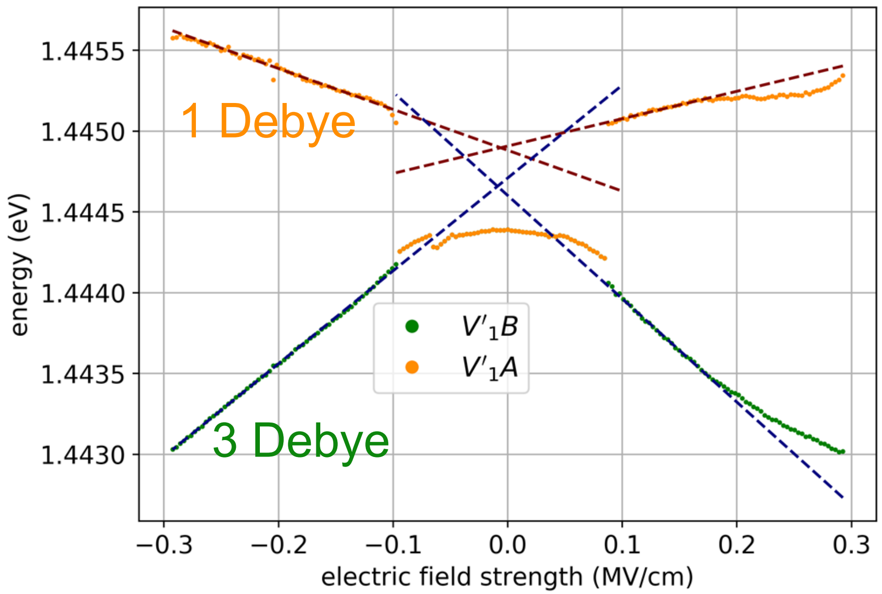


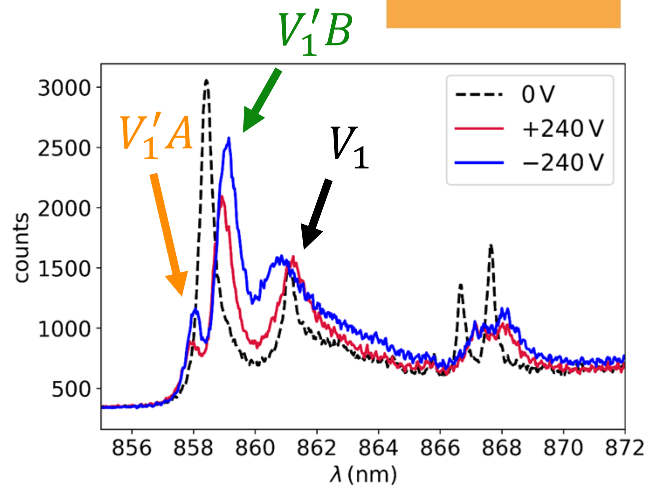
Problems with fits due to overlapping peaks

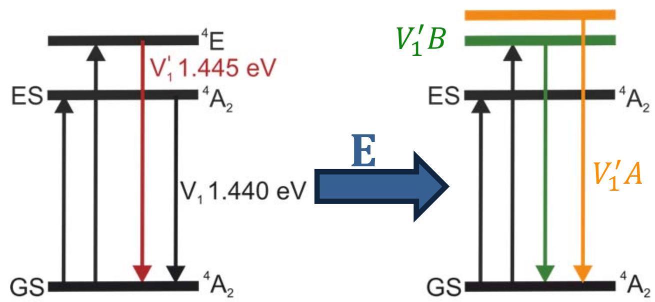
Between fingers: Stark effect

	$V'_1\,A$	$V'_1\,B$	NV-center
μ (Debye)	1	3	1.5

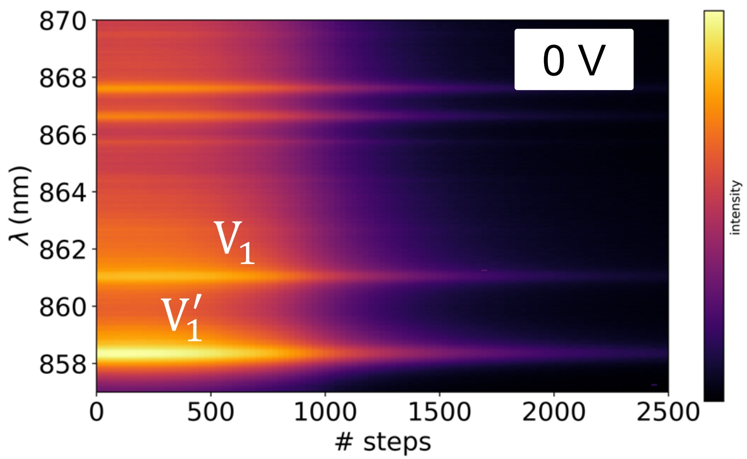
Tamarat, Ph, et al. *Physical review letters* 97.8 (2006): 083002.

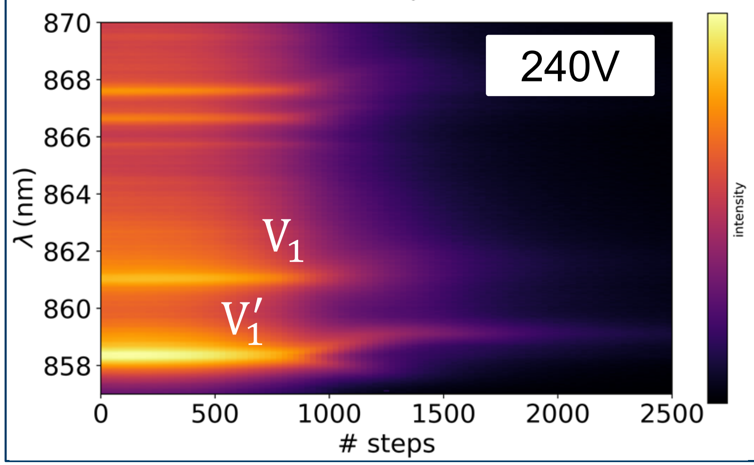




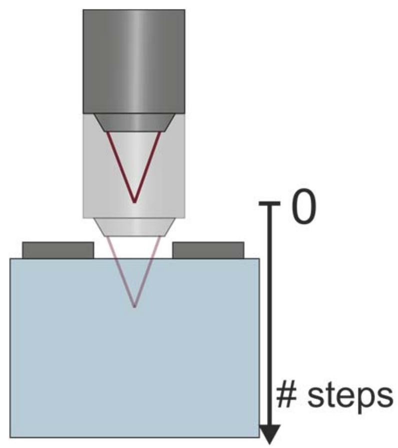


Between fingers: z-scan

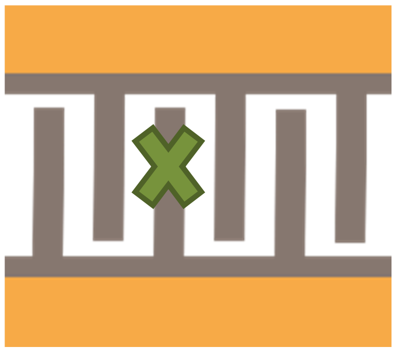




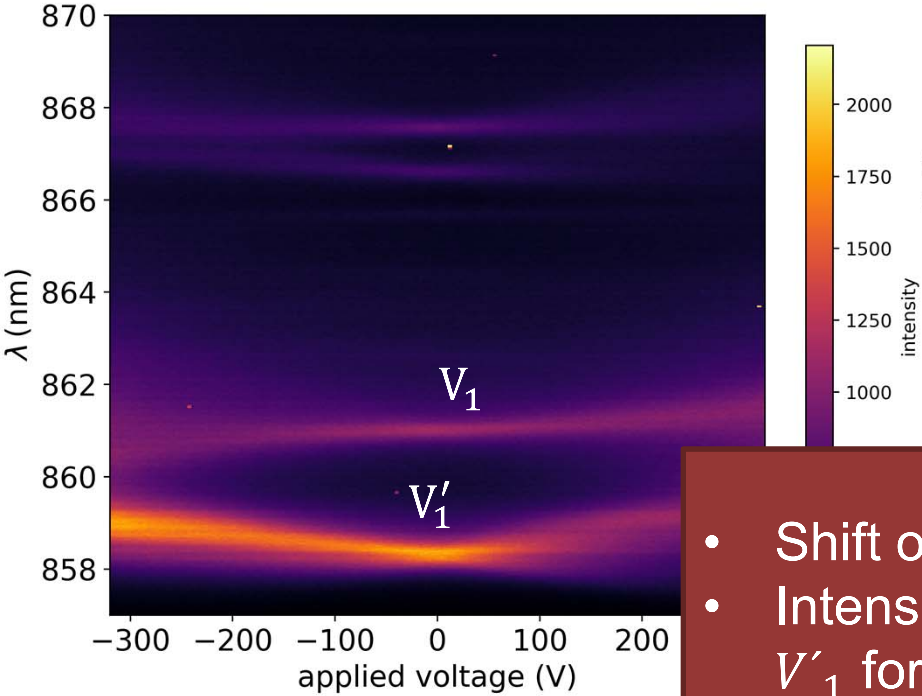
- Clear influence of electric field
- Splitting of V_1' at certain depth
- Also for large # steps still difference between 0V and 240V

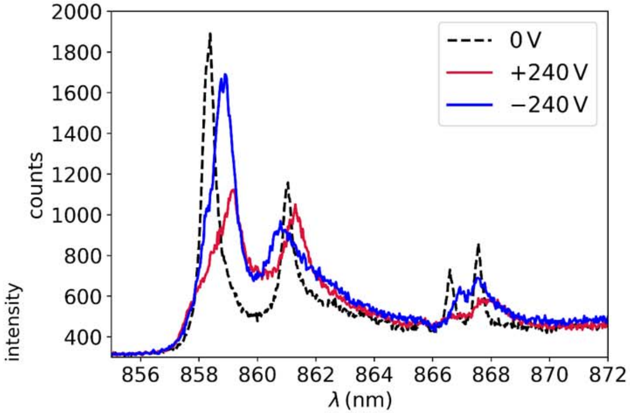


Measurement below finger



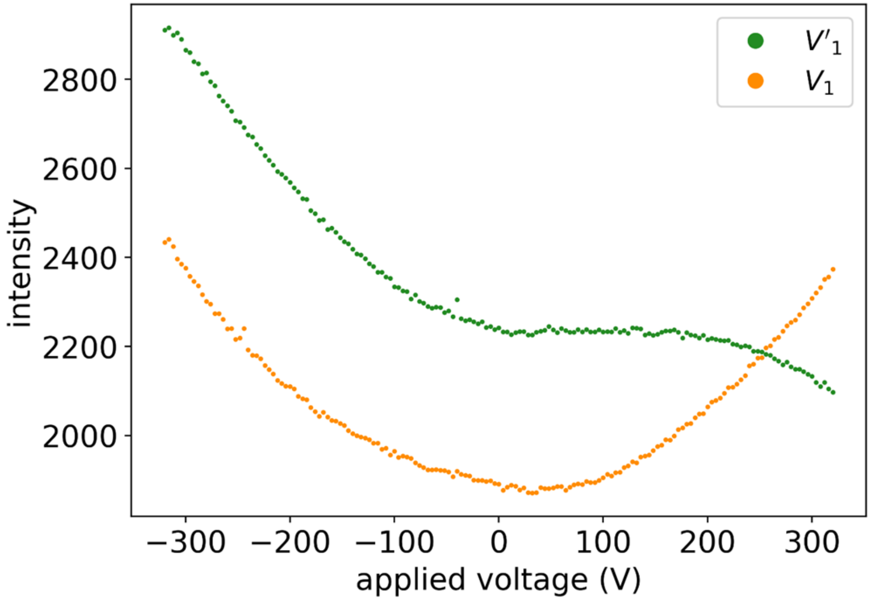
Below finger: Voltage sweep

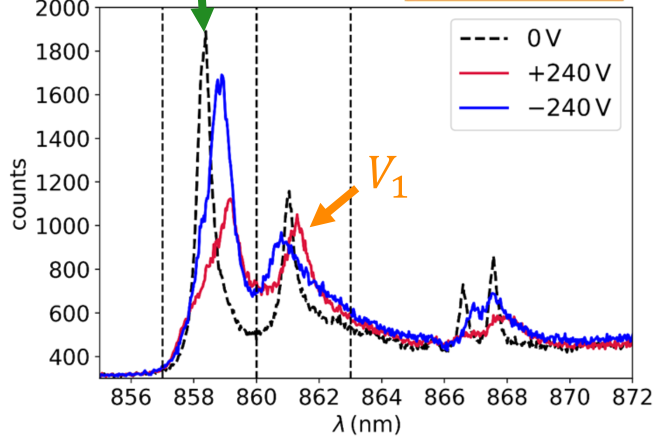


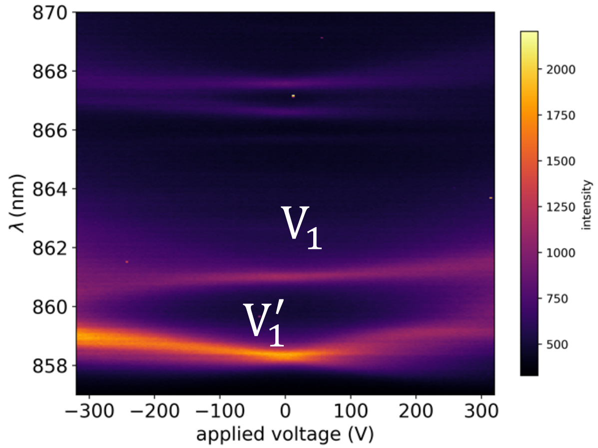


- Shift of V'_1 and V_1
- Intensity difference of V'_1 for $\pm V$

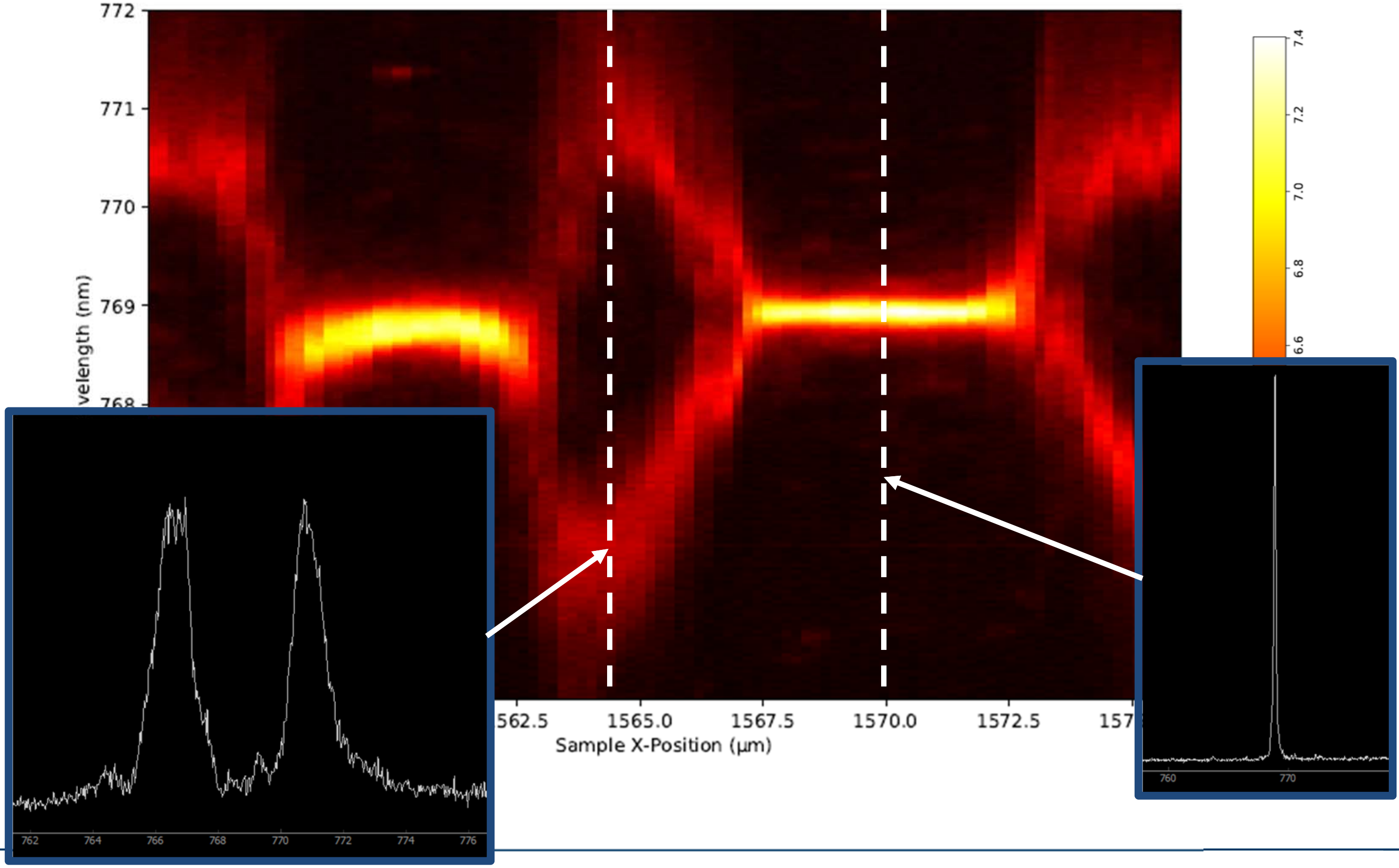
Below finger: Voltage sweep

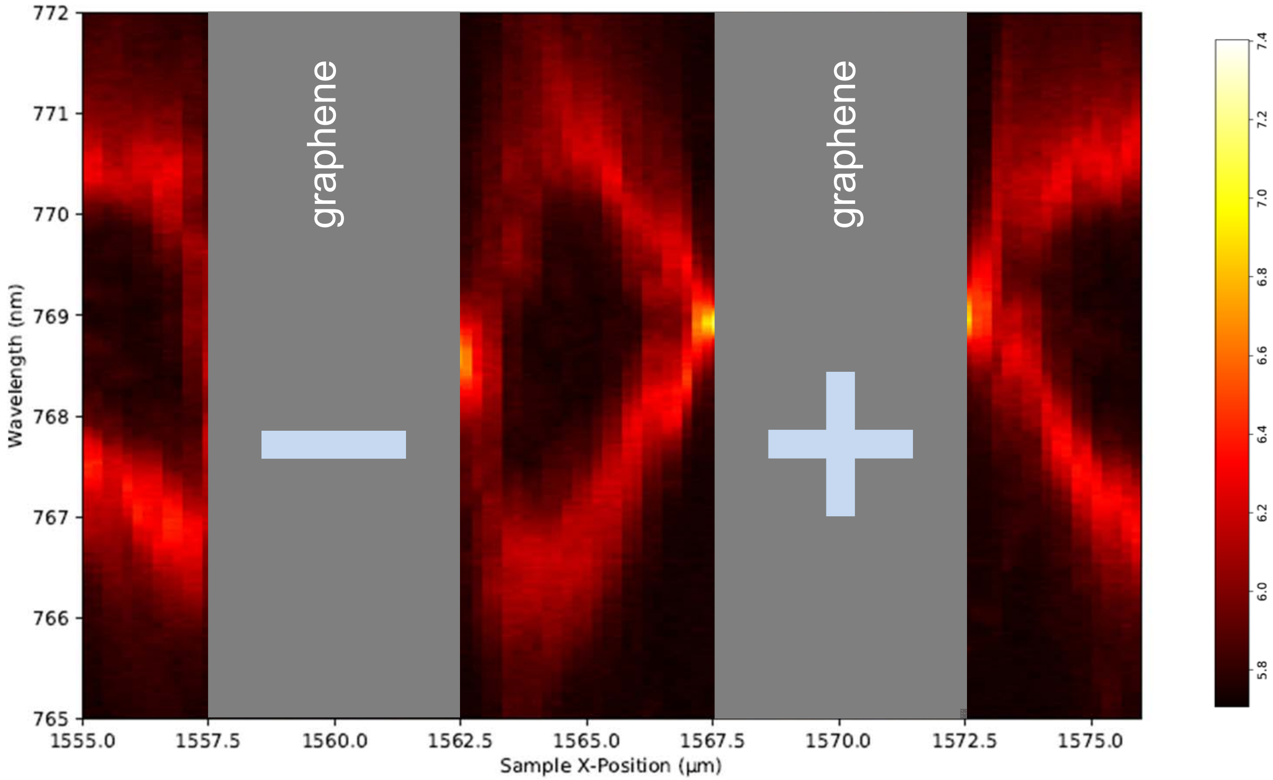




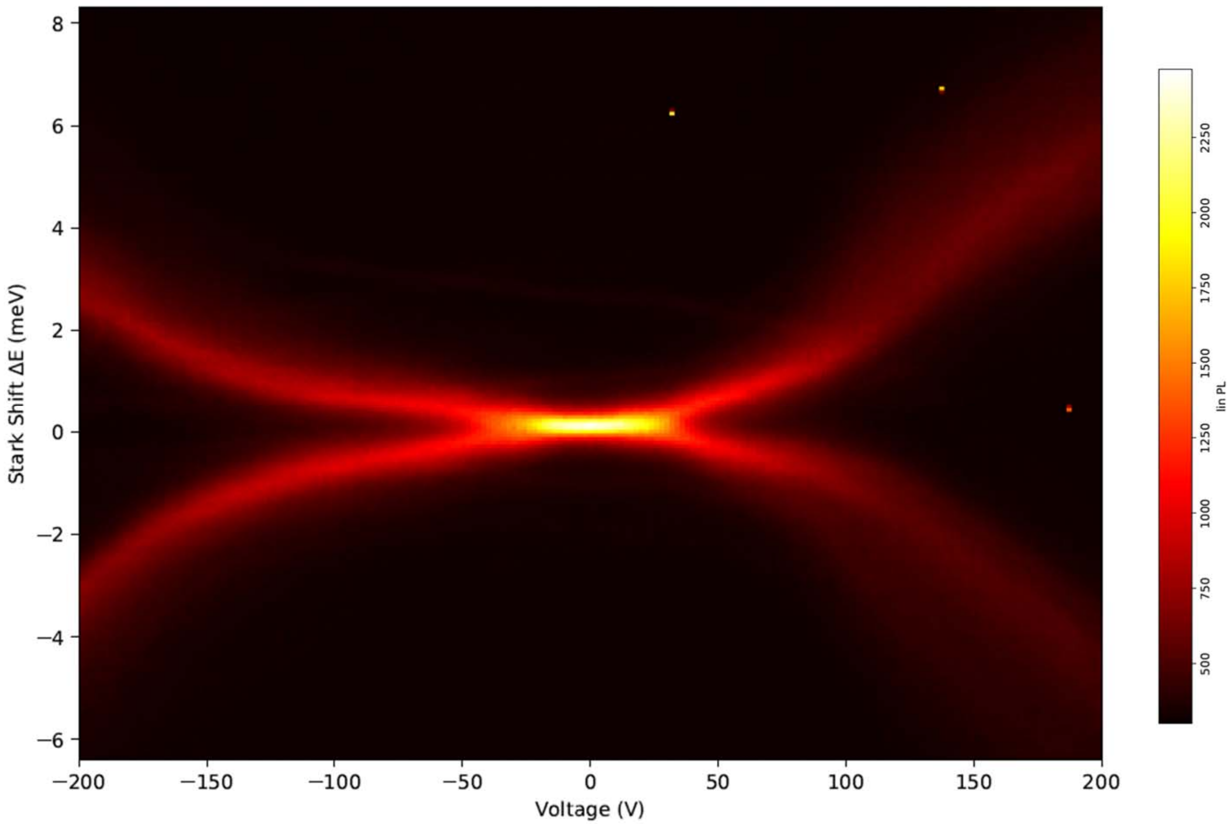


The yet unknown TS defect: huge Stark shift





772
771
770
769
768
767
766
765
Wavelength (nm)
graphene
graphene
1555.0
1557.5
1560.0
1562.5
1565.0
1567.5
1570.0
1572.5
1575.0
Sample X-Position (µm)
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8

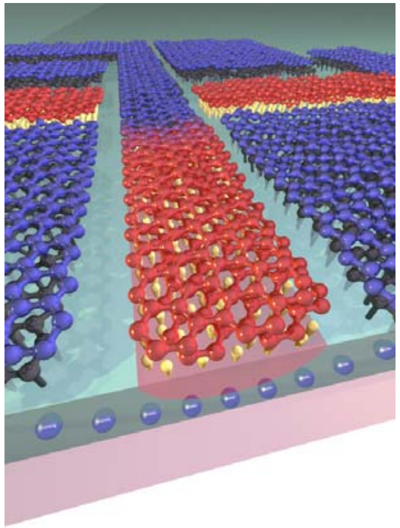

Stark Shift ΔE (meV)
8
6
4
2
0
−2
−4
−6
−200
−150
−100
−50
0
50
100
150
200
Voltage (V)
lin PL
500
750
1000
1250
1500
1750
2000
2250

With the material system Epitaxial Graphene on Silicon Carbide one can advance into so far unattainable physical regimes

Physics in the graphene plane

The graphene/SiC system: a Schottky junction

Physics in SiC: Colour centres



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Thank you very much for your attention!