Quantum Hall effect in hydrogenated graphene

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Why?

- Understanding graphene and the effect of hydrogen on the system
  - If we know the band structure, we can predict behaviour
- Low resistivity to limit potential differences
  - Influenced by temperature, magnetic field and doping
  - Fully hydrogenated graphene is an insulator

Why & how?

- Understanding graphene and the effect of hydrogen on the system
  - If we know the band structure, we can predict behaviour
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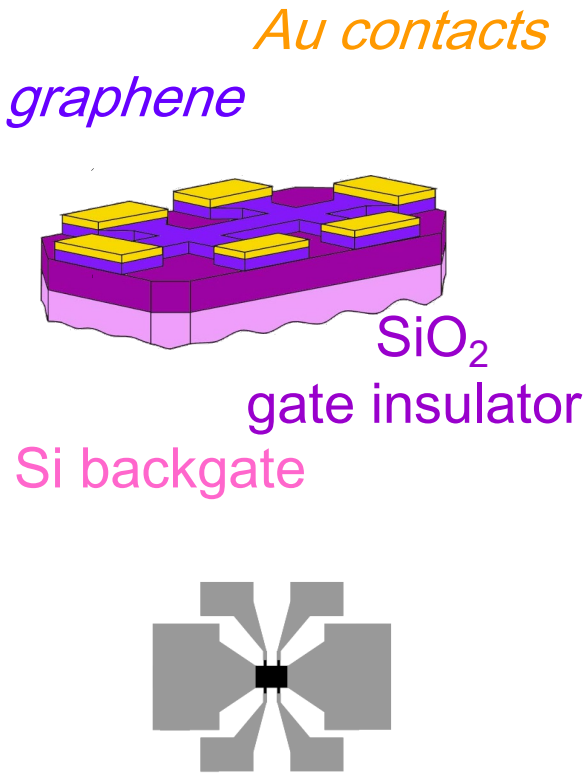
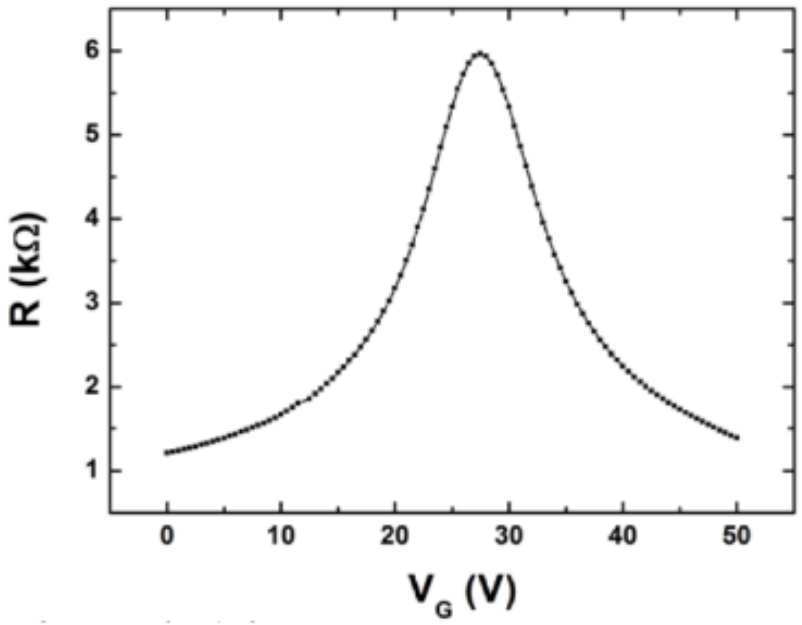
  - Influenced by temperature, magnetic field and doping
  - Fully hydrogenated graphene is an insulator

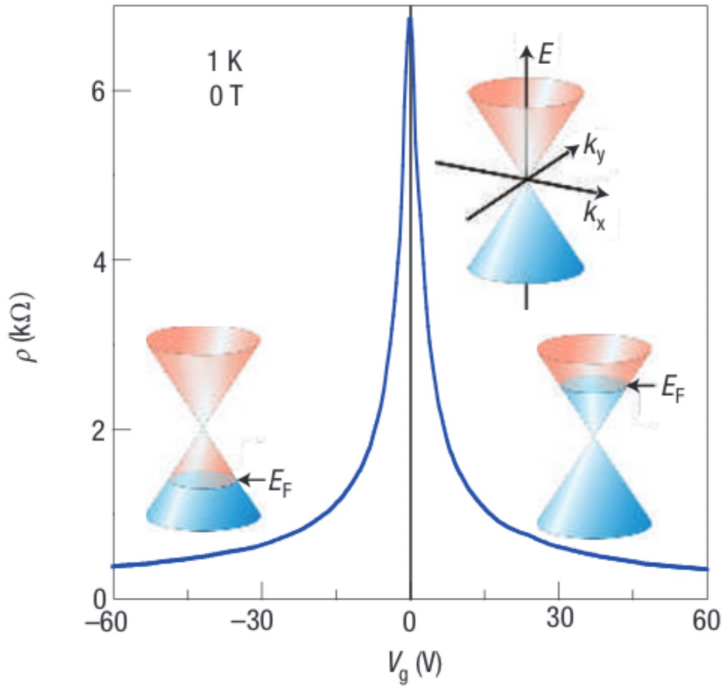
- Temperature dependence
- Magnetic field effects
- Band structure simulations

Graphene Field Effect Transistor





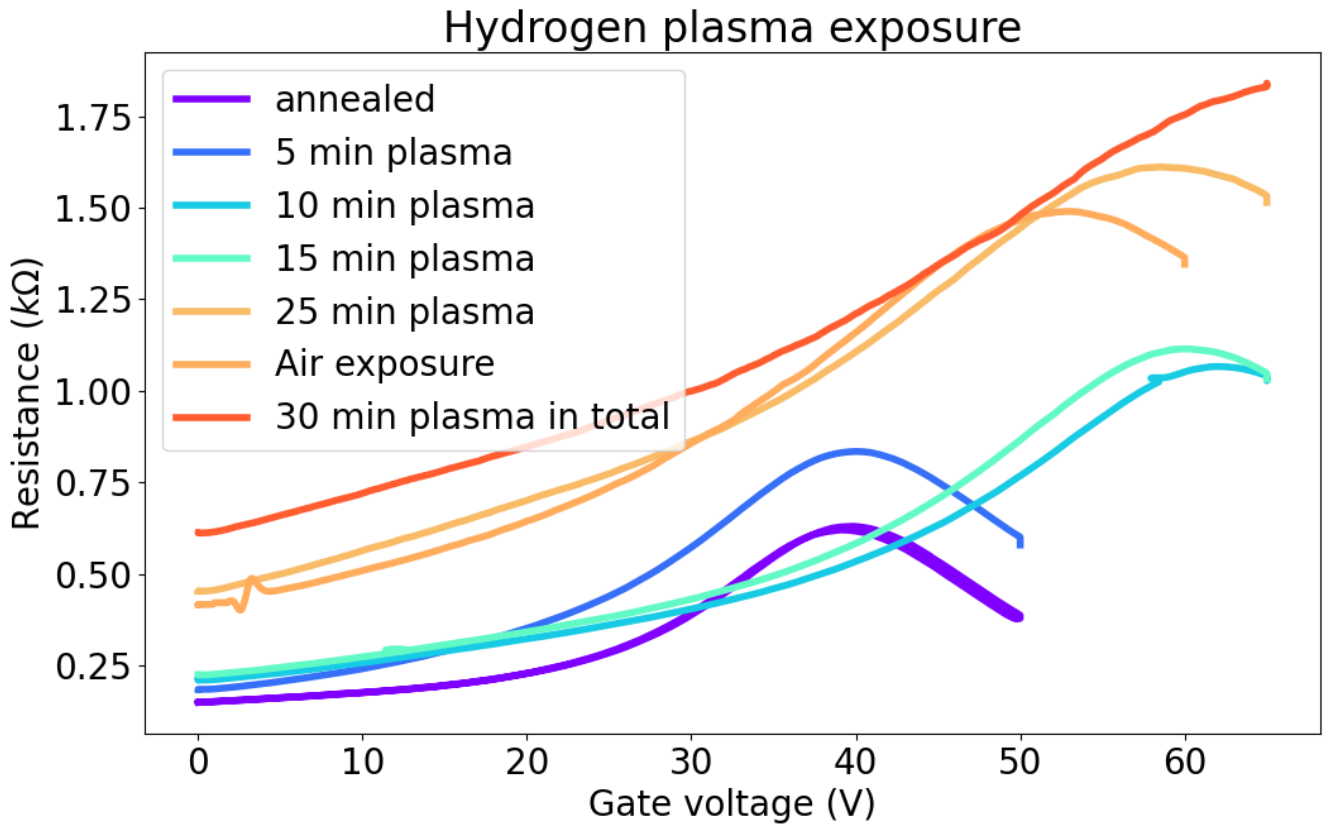
Graphenea, GFET-S10 data sheet



Geim, A. K. & Novoselov, K. S. The rise of graphene. In Nanoscience and technology: a collection of reviews from nature journals, 11–19 (World Scientific, 2010)

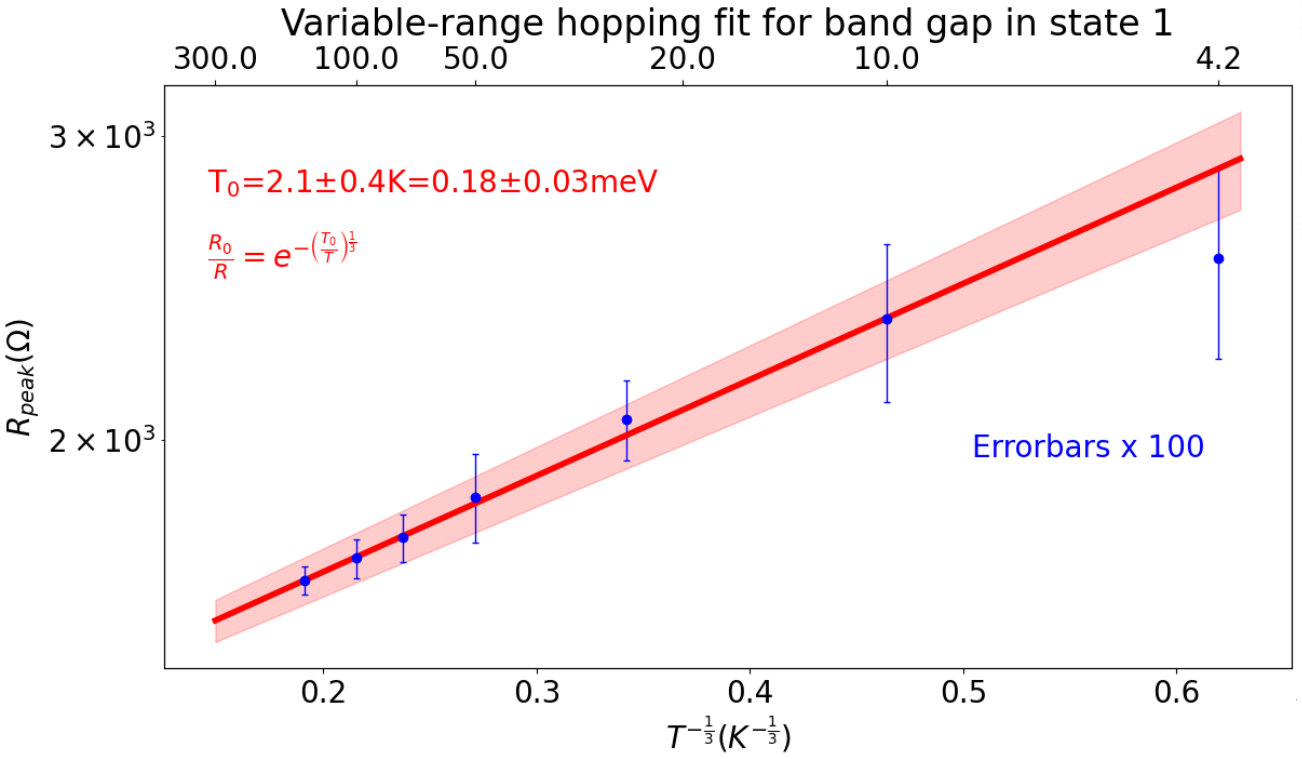
Hydrogenation process

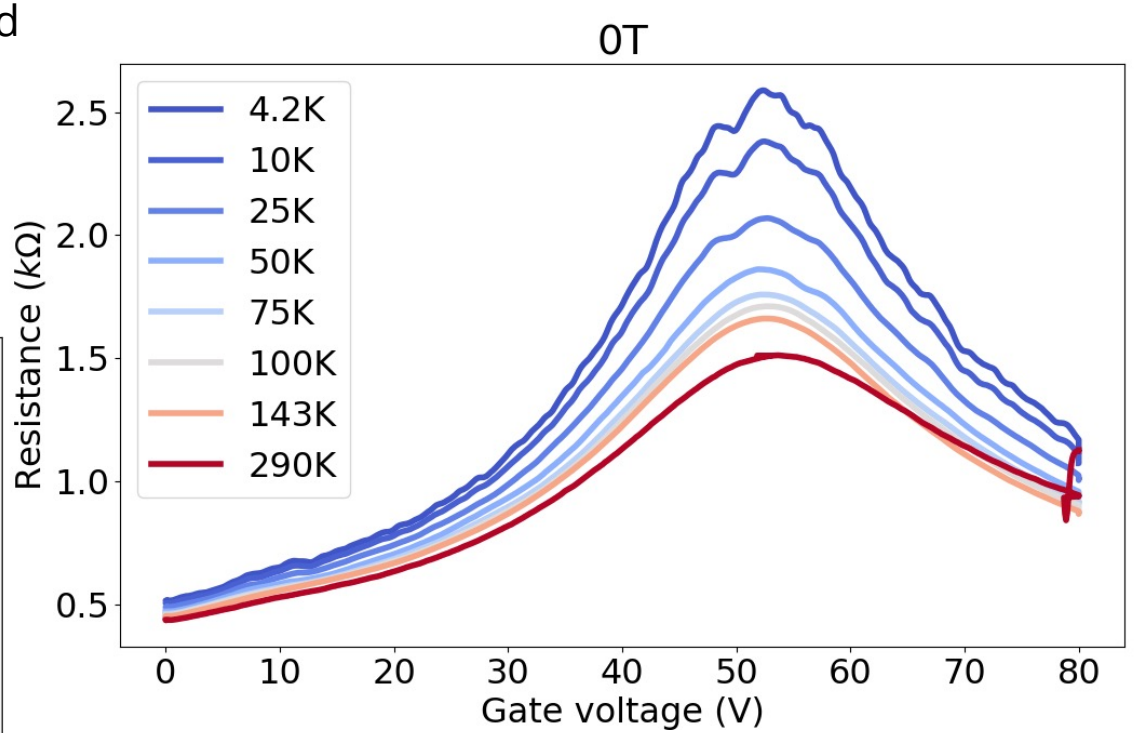
- Start with annealed sample
- Exposed 1 mbar hydrogen plasma for 5 minutes
- Exposed to air for 10 minutes
- Repeat until we reach the wanted state



Temperature dependence

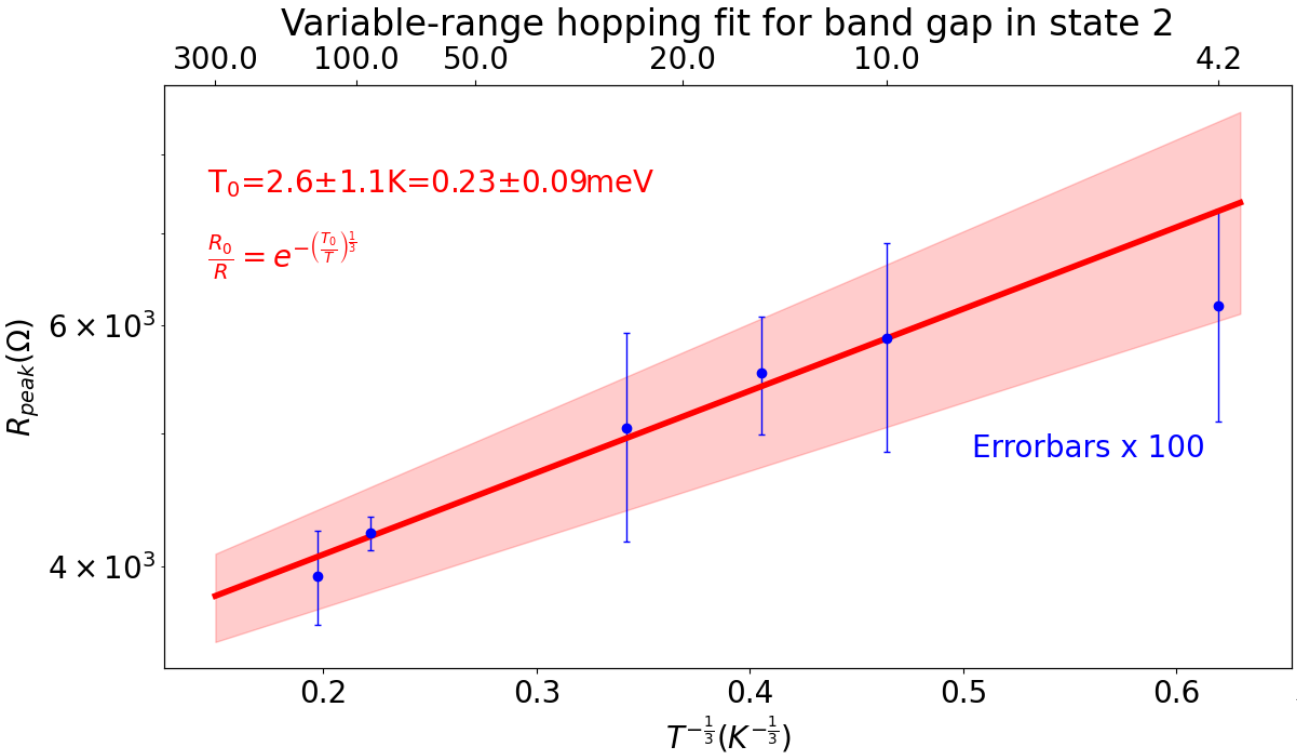
- Peak resistance increased as temperature decreased
- Pristine state: no temperature dependence
- From vrh fit: band gap 2.1±0.4K

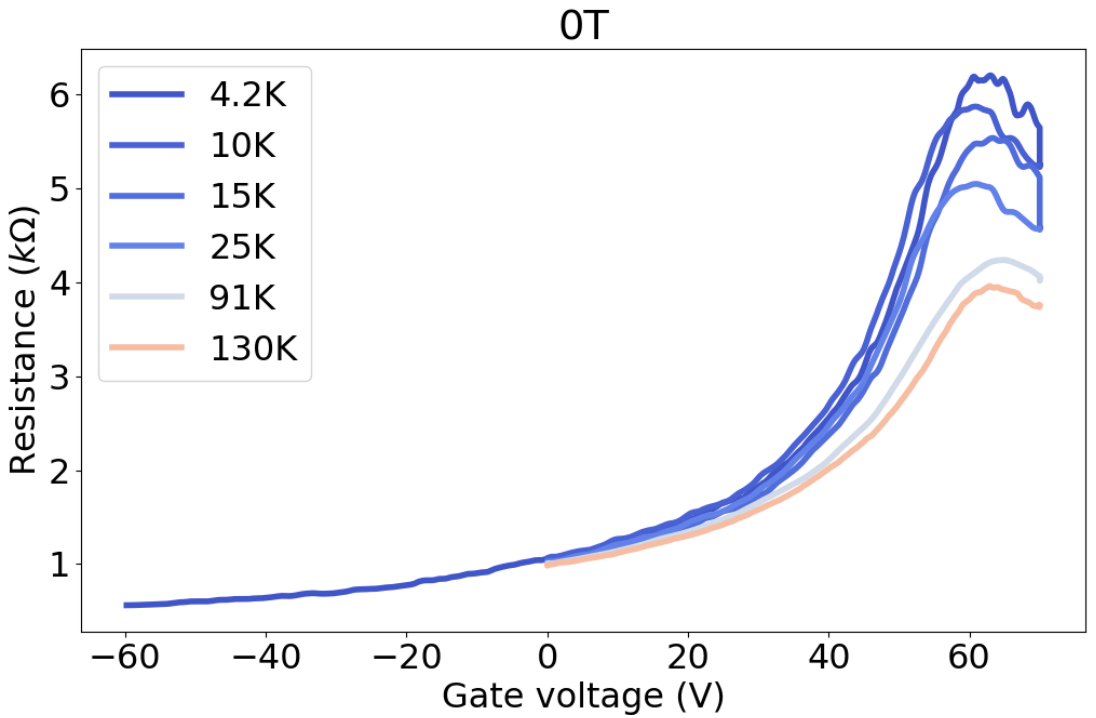




Temperature dependence

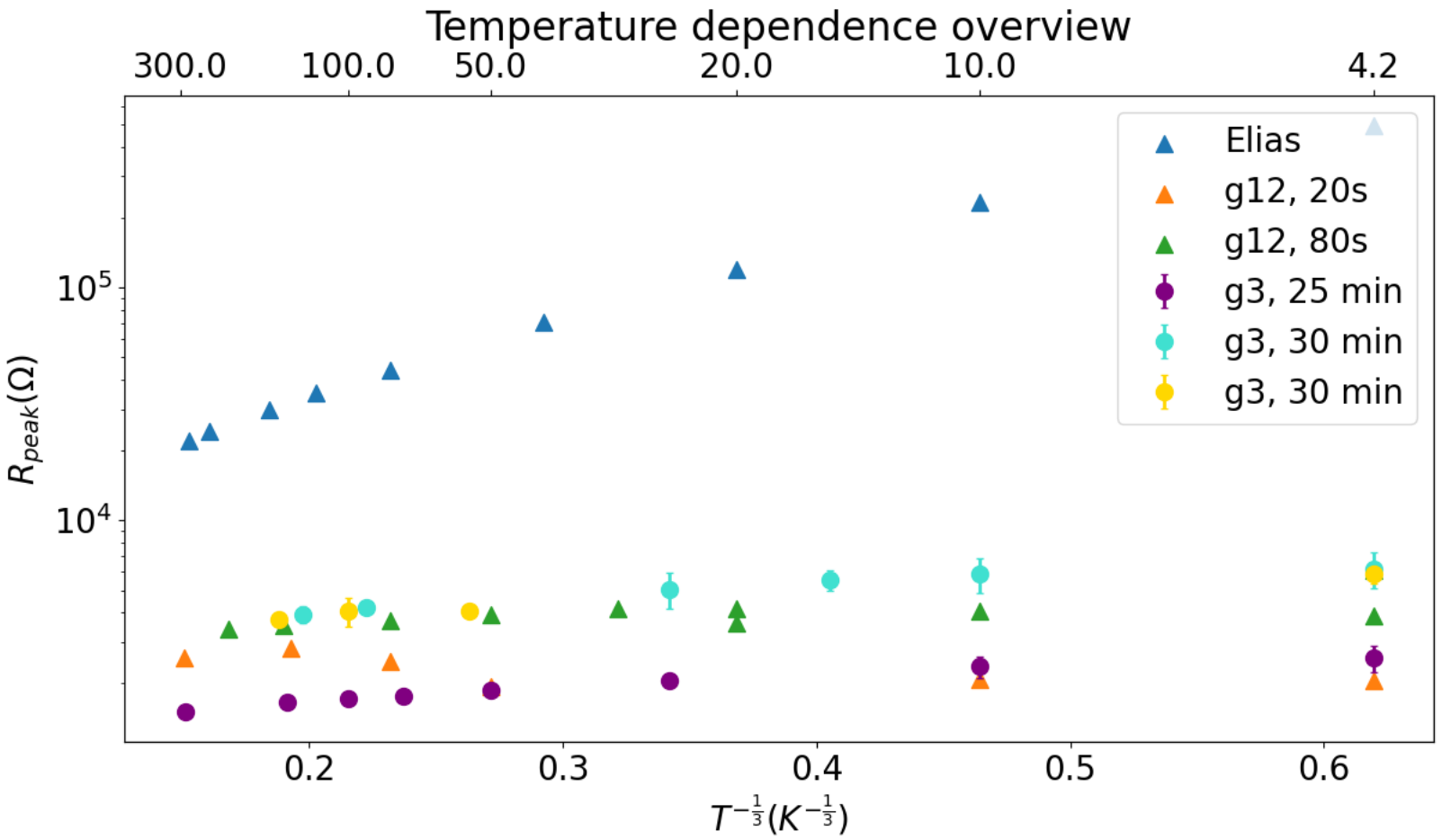
- Neutrality point shifted
- Temperature dependence similar
- From vrh fit: band gap 2.6±1.1K



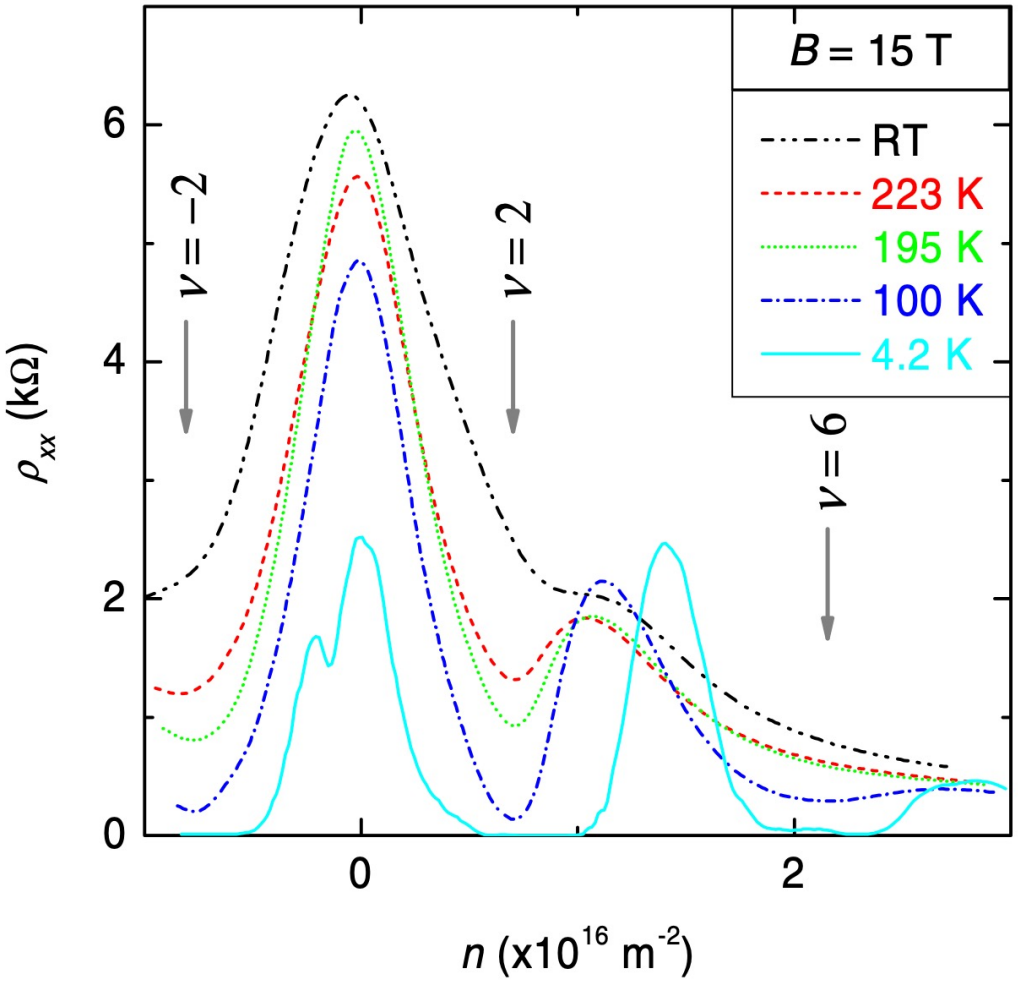


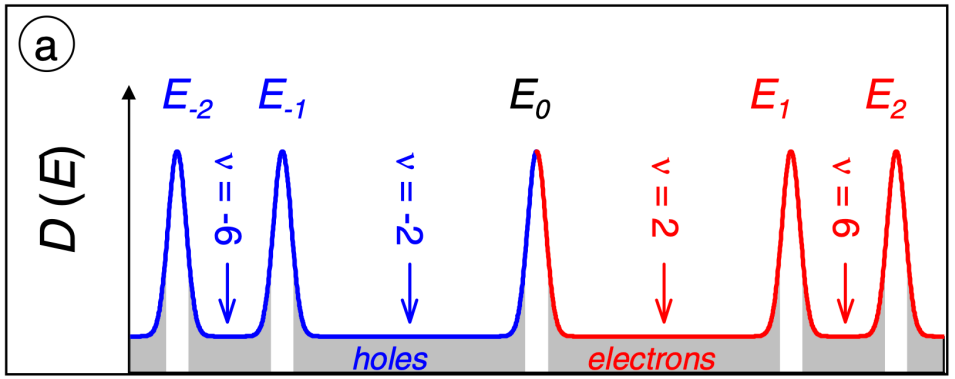
Temperature dependence

- Compare samples g12 and g3
- Similar band gap opening
- Band gap is far smaller than for a fully hydrogenated graphene sample (Elias *et al.*, Science **323**, 610-613 (2009))



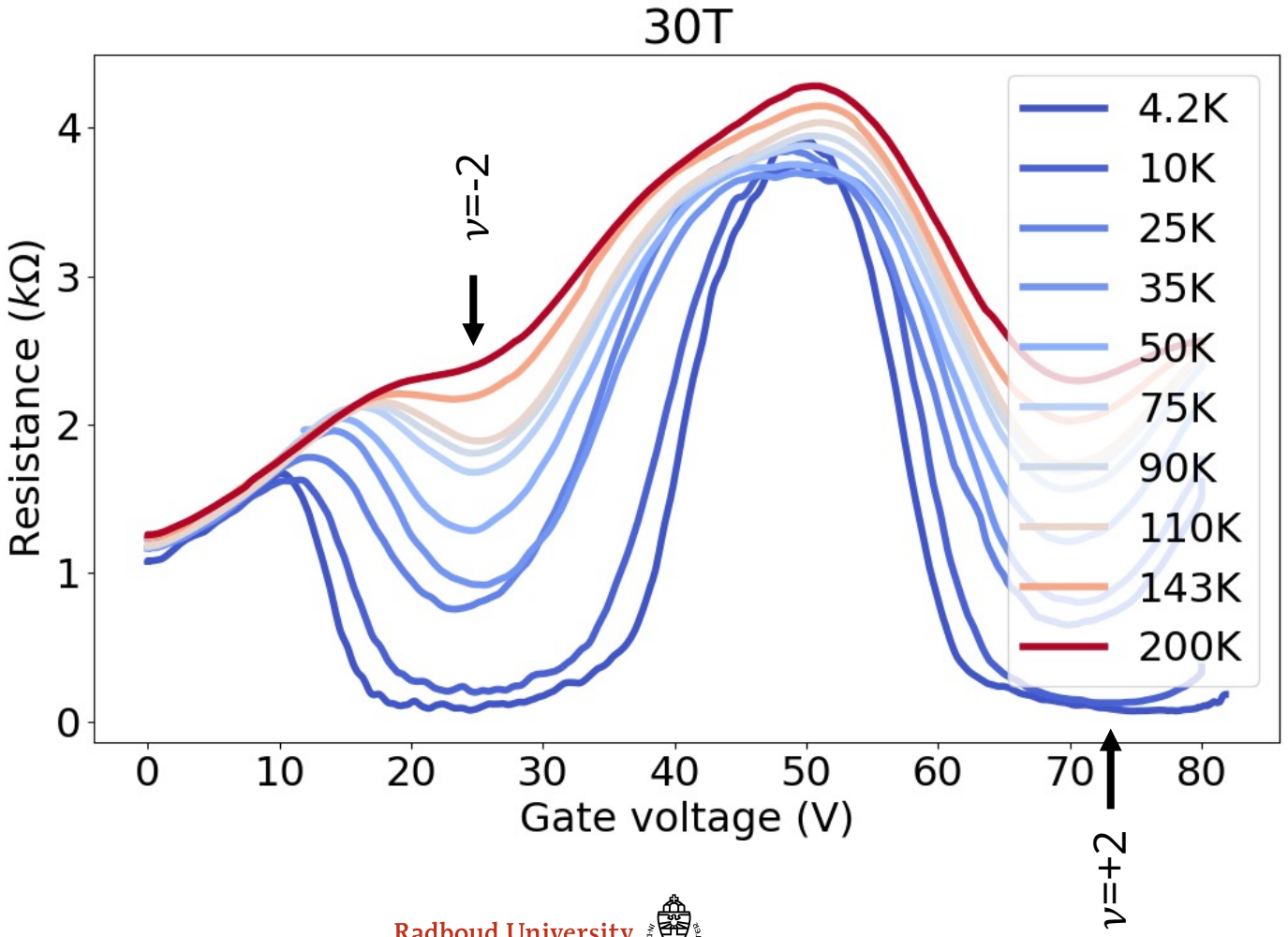
Magnetic field effects



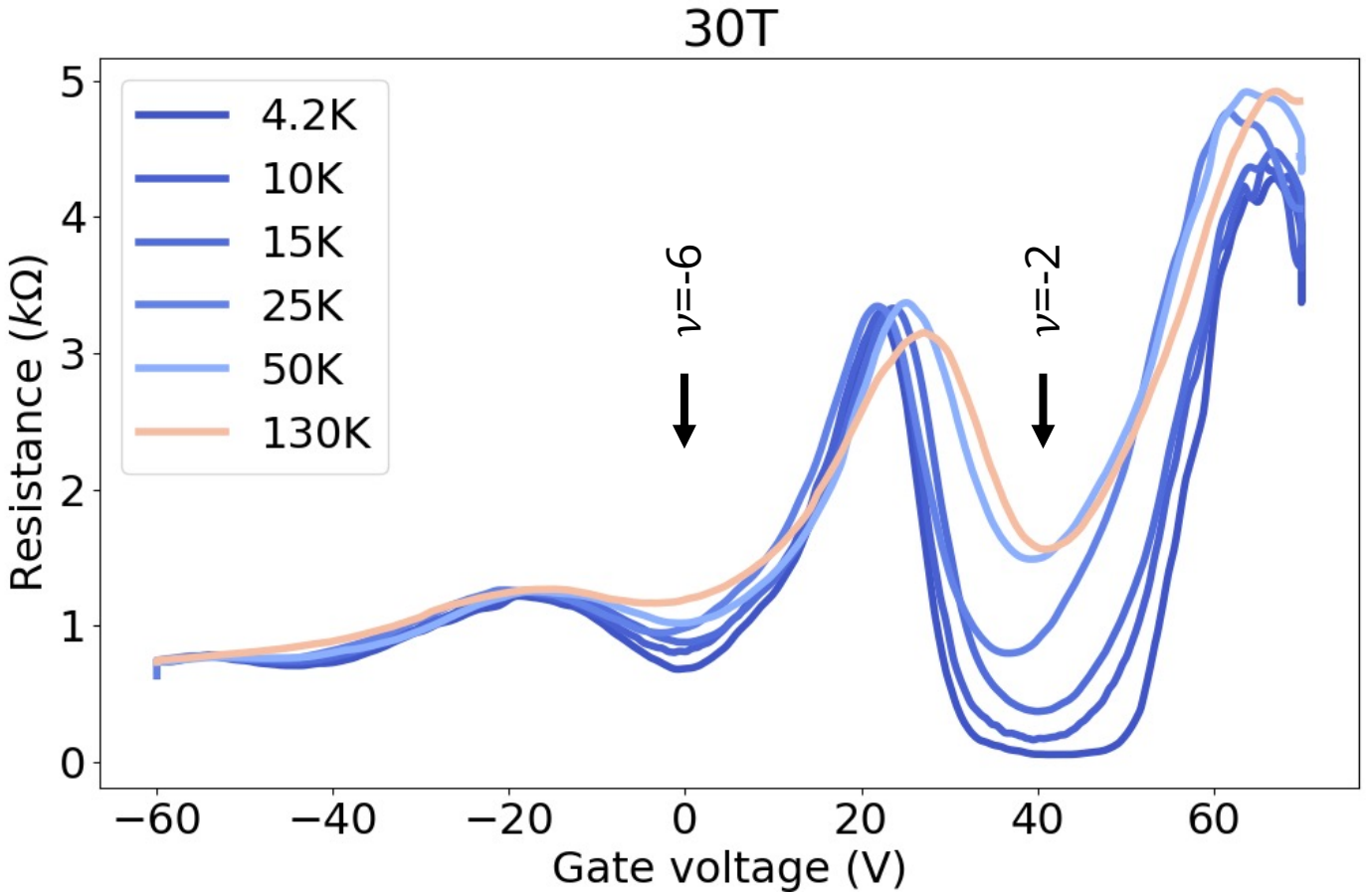


A. J. M. Giesbers, U. Zeitler, M. I. Katsnelson, L. A. Ponomarenko, T. M. Mohiuddin, and J. C. Maan, Quantum-Hall Activation Gaps in Graphene. In PRL 99, 206803 (2007)

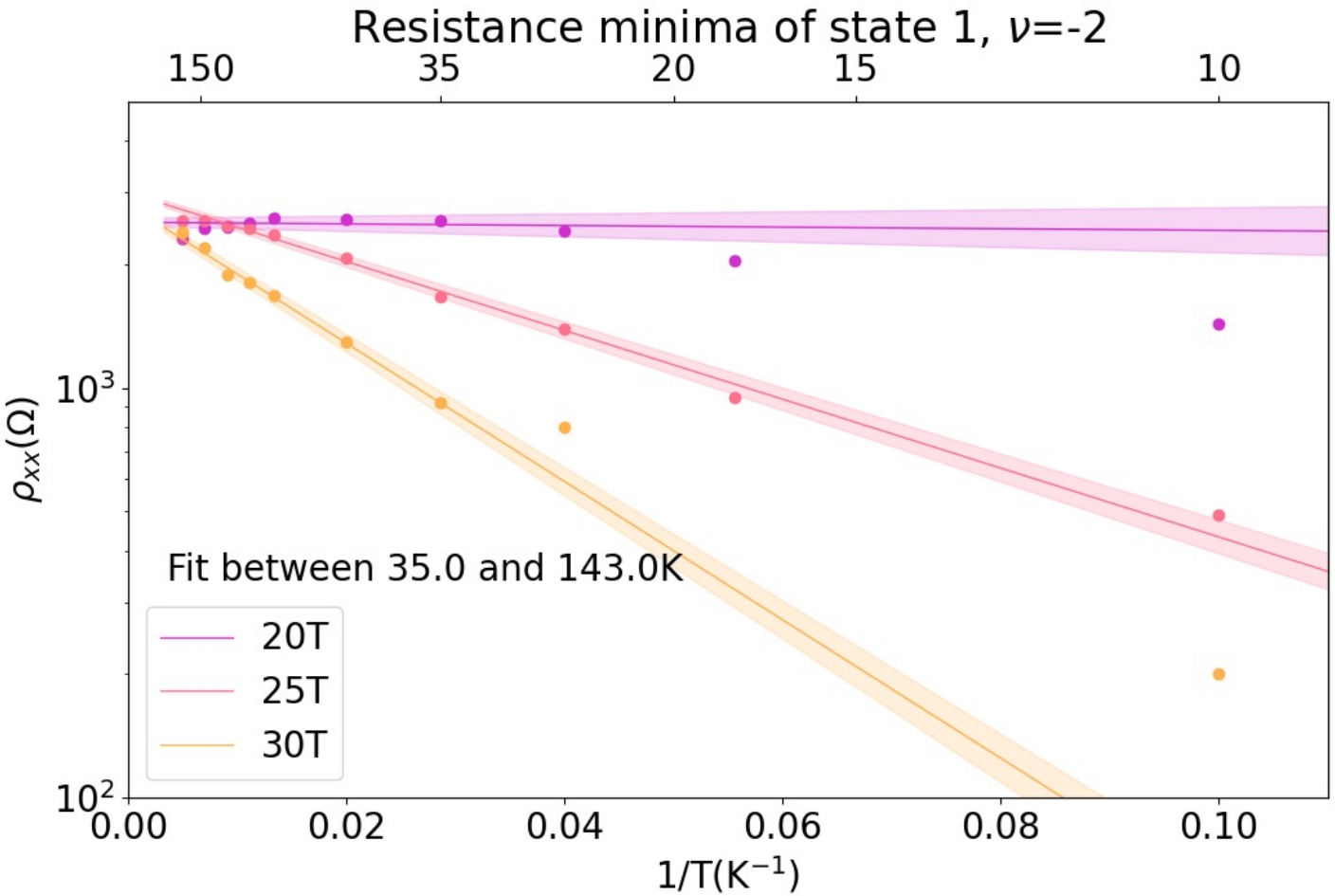
Quantum Hall Effect

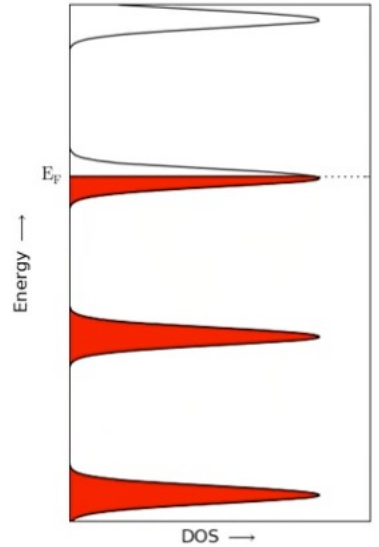


Quantum Hall Effect



Activation energy

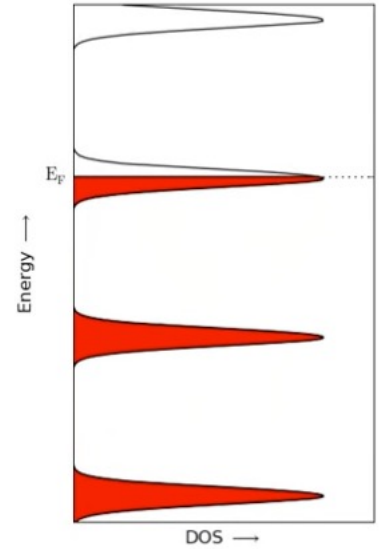


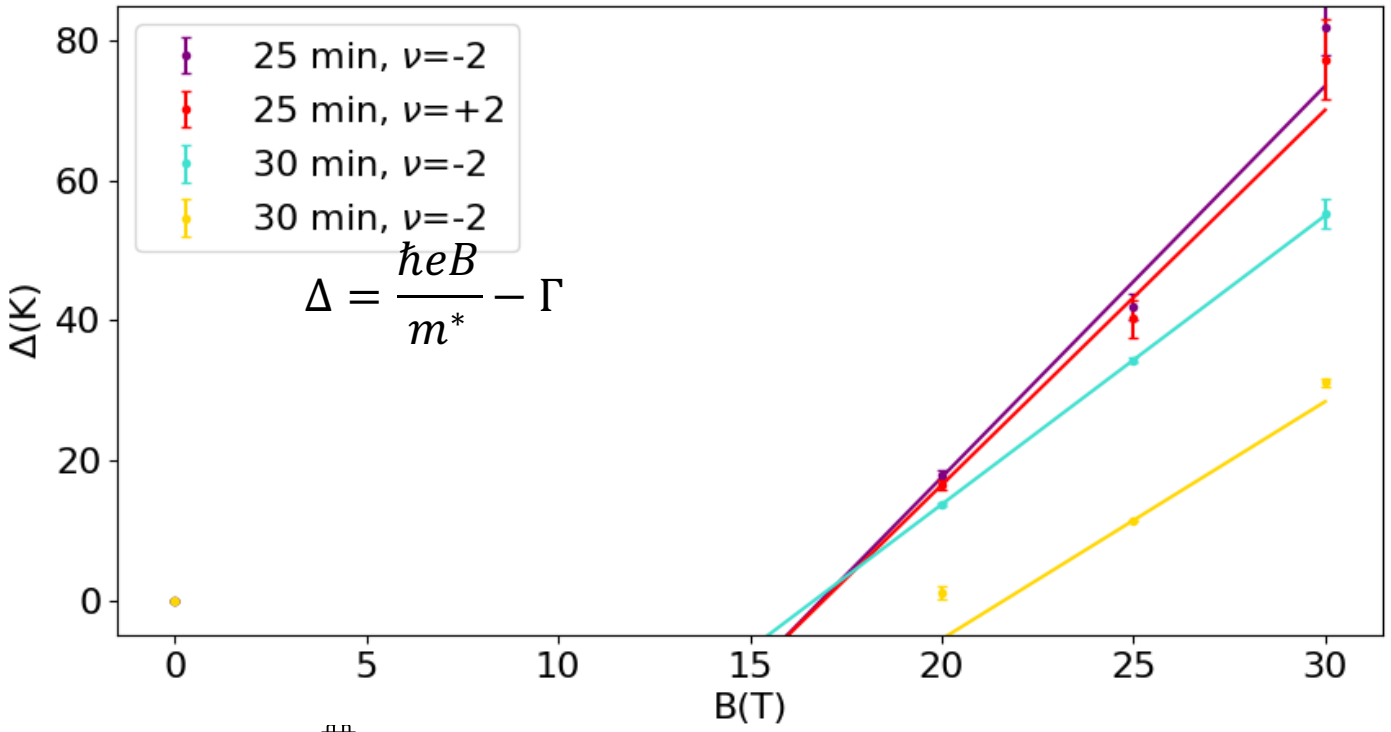


$$R \propto exp(-\Delta_a/k_B T)$$

Activation energy

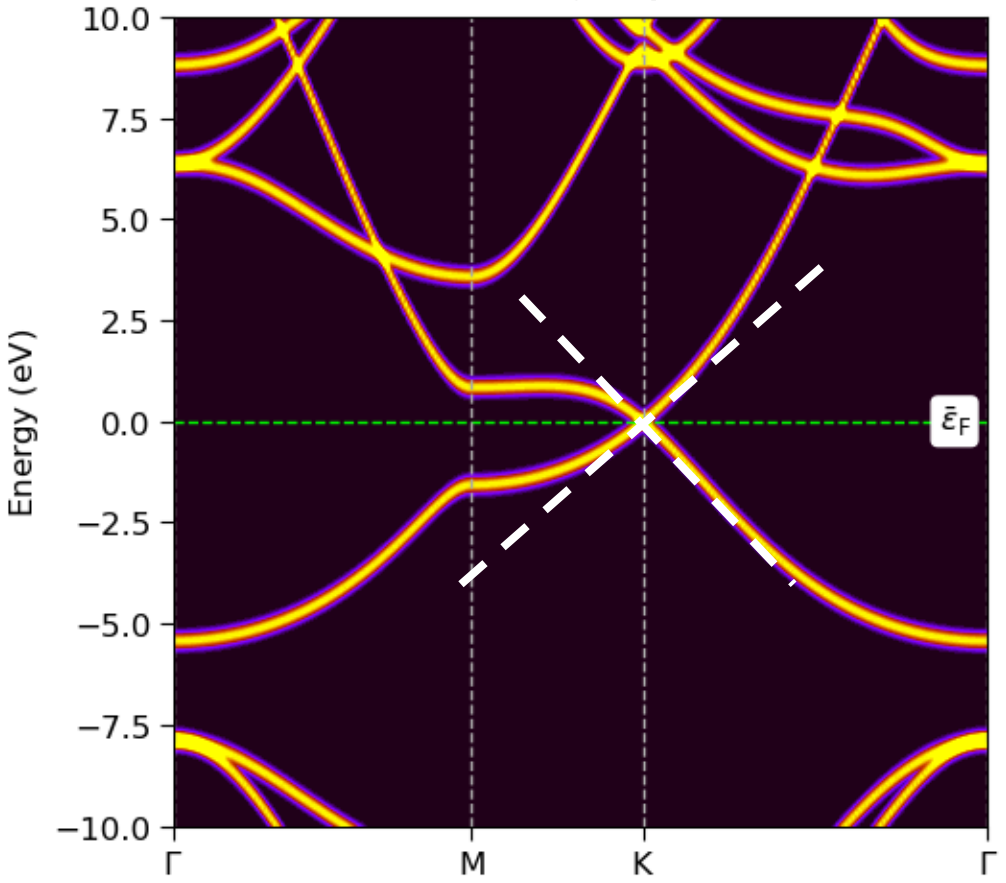
- Activation gap depends on Landau level broadening and peak-to-peak distance
- Effective electron mass can be extracted from the slope of the activation gap
- 25 minutes of plasma exposure, filling factor -2: $m^* = 0{,}24 \pm 0.04\, m_e$
- 30 minutes of plasma exposure, filling factor -2: $m^* = 0{,}4 \pm 0.1\, m_e$
- For pristine graphene, $\Delta \propto \sqrt{B}$



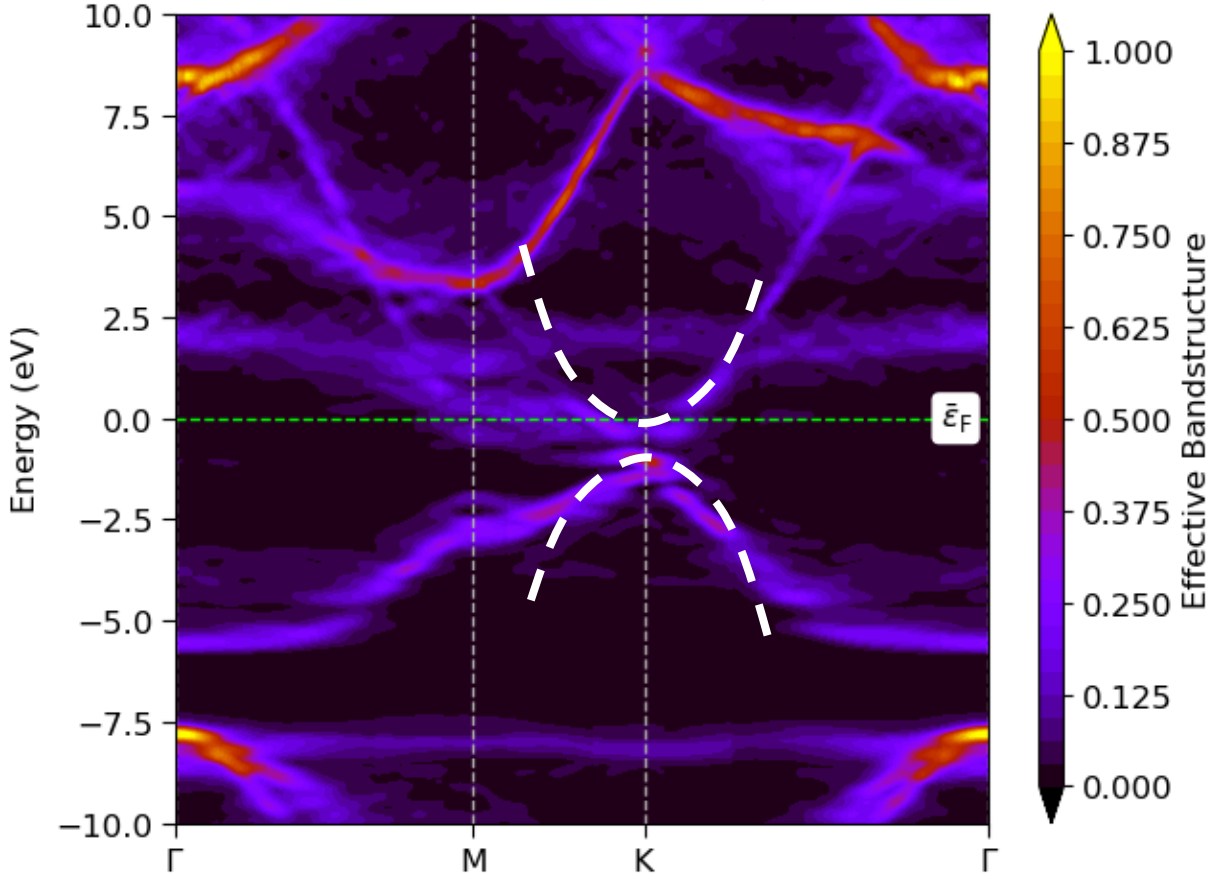


Simulations

Pristine graphene



12.5% H coverage



Simulations

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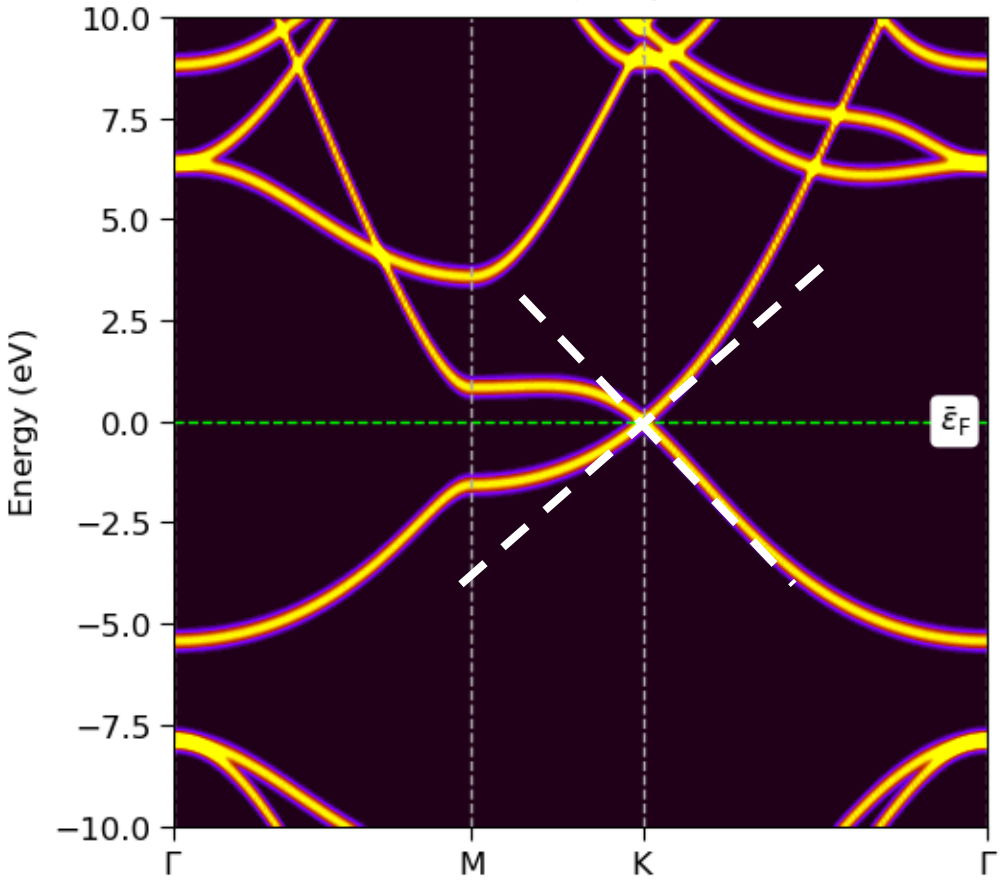
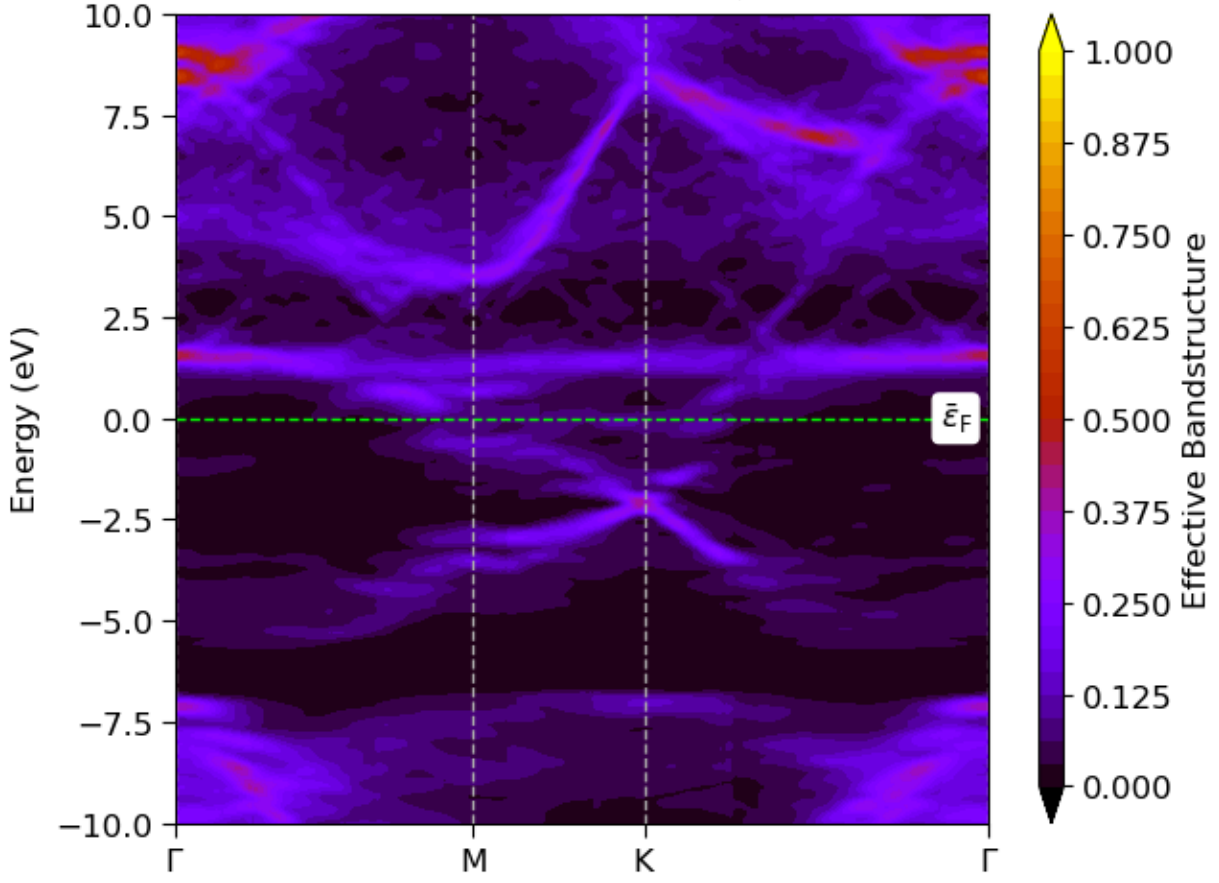
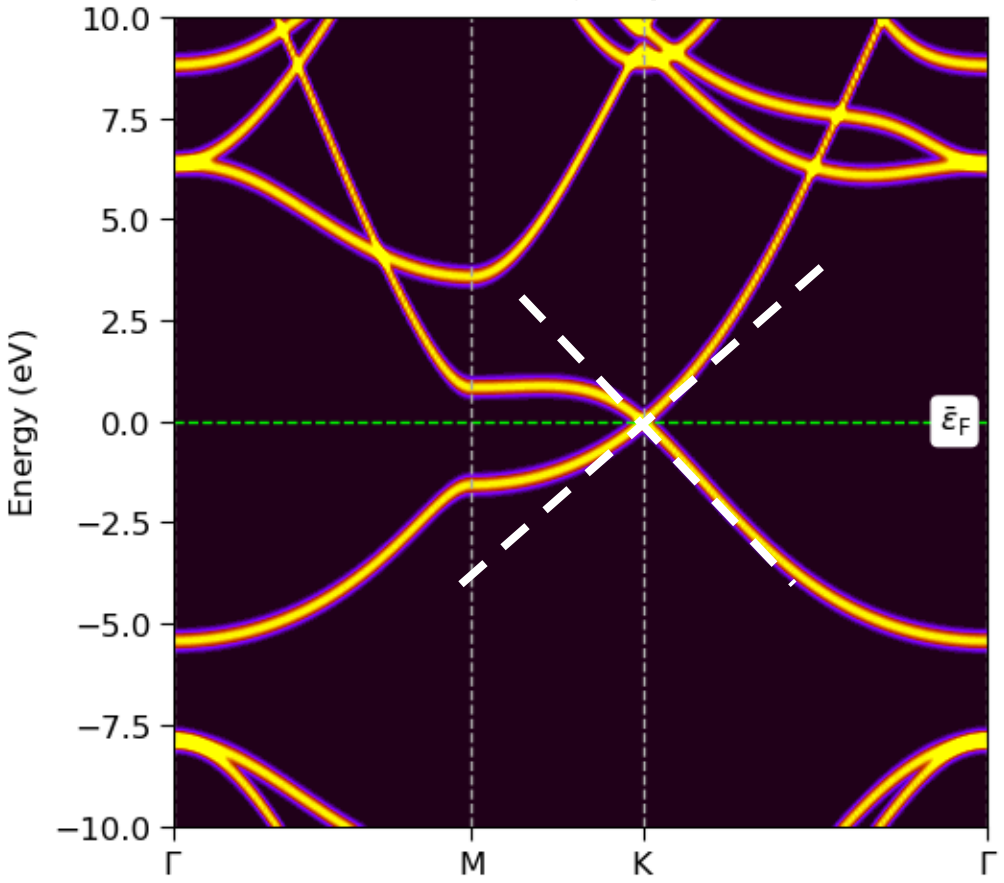


25% H coverage

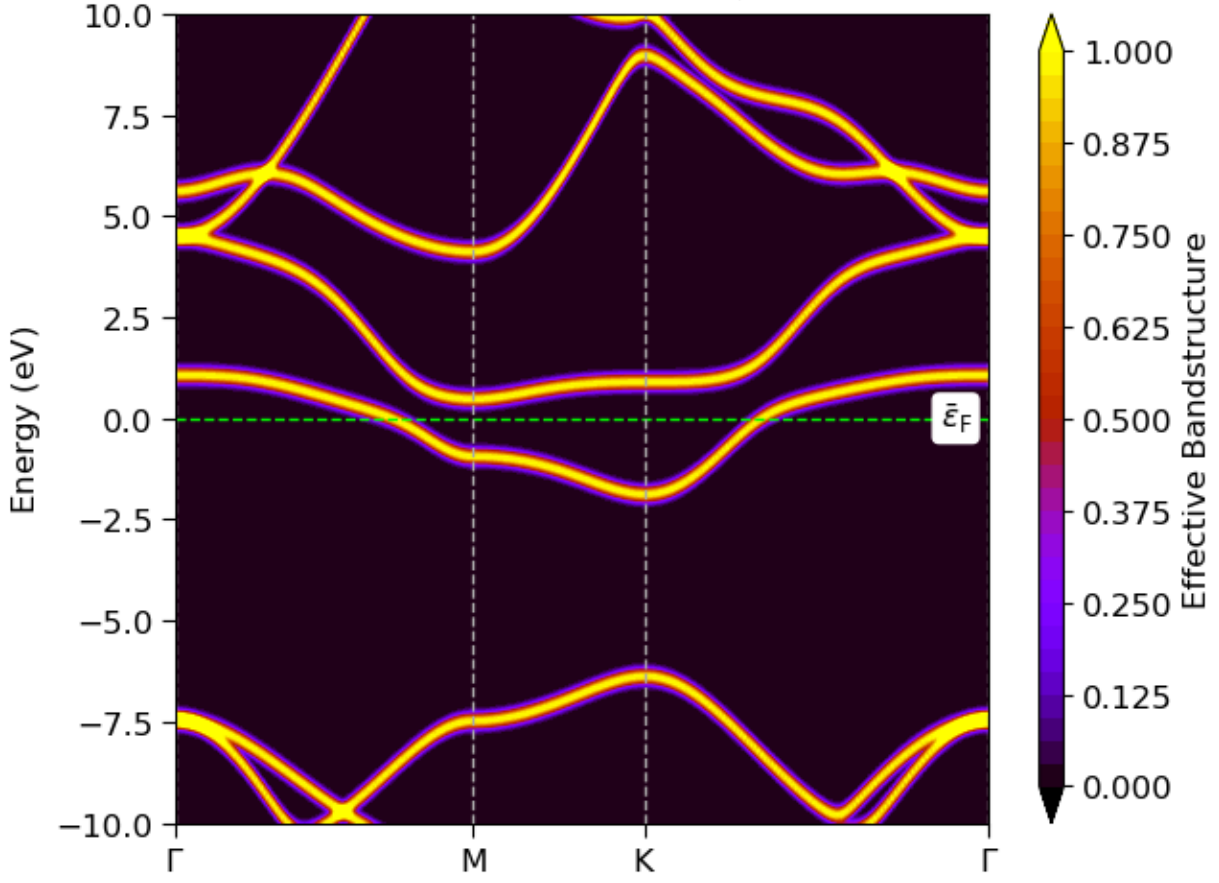


Simulations

Pristine graphene



50% H coverage



Implications for PTOLEMY

- H-graphene resistance depends on temperature, magnetic field, electric field, doping and coverage
- A small electric field at the target might help reduce the resistance, and the risk of potential differences on the surface, significantly
- We might be able to reduce the resistance by doping the sample or applying a electric field

Implications for PTOLEMY

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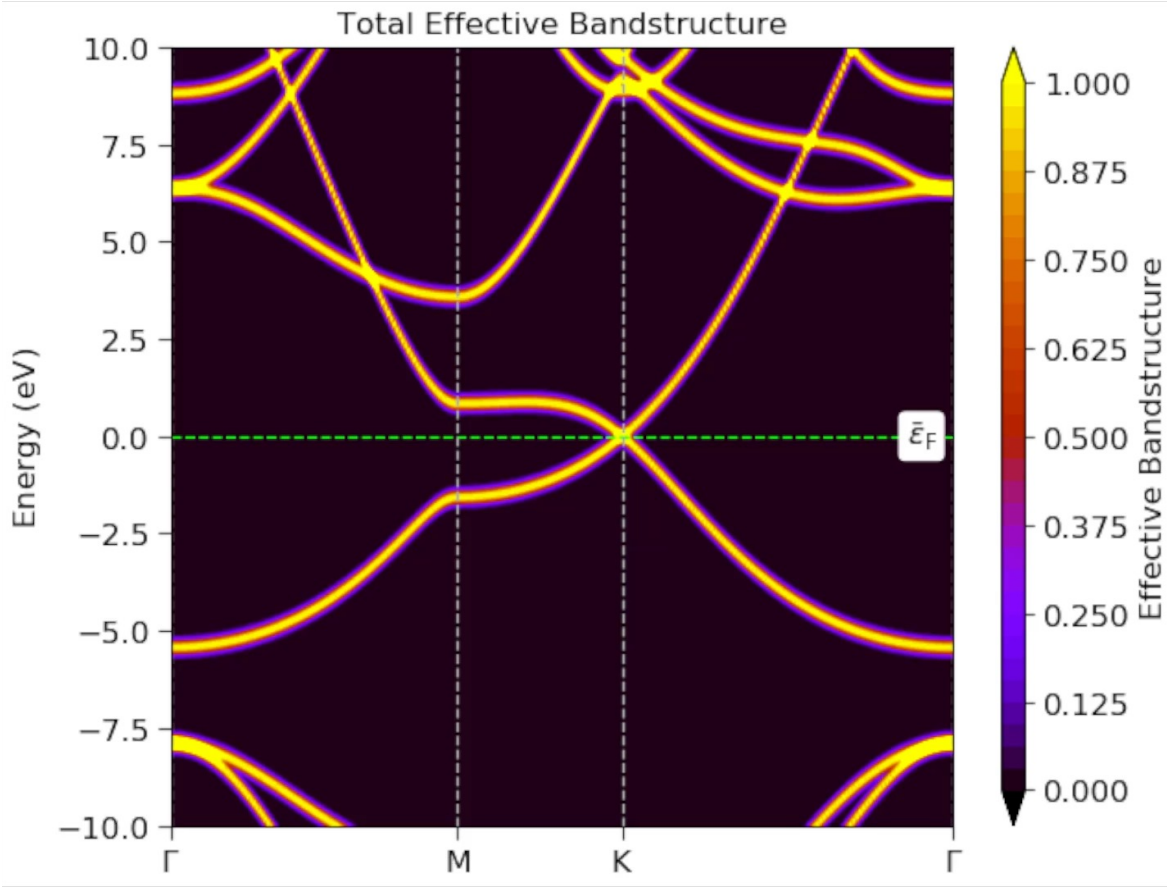
- Contact with KIT for tritium measurements

BACKUP SLIDES


Total Effective Bandstructure
Energy (eV)
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
Γ
M
K
Γ
$\bar{\varepsilon}_F$
1.000
0.875
0.750
0.625
0.500
0.375
0.250
0.125
0.000
Effective Bandstructure

Quantum hall resistance

- $\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2}$
- Only localised states:
  - $\sigma_{xx} = 0$
  - σ_{xy} finite

The Nijmegen Group

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Thomas Derks
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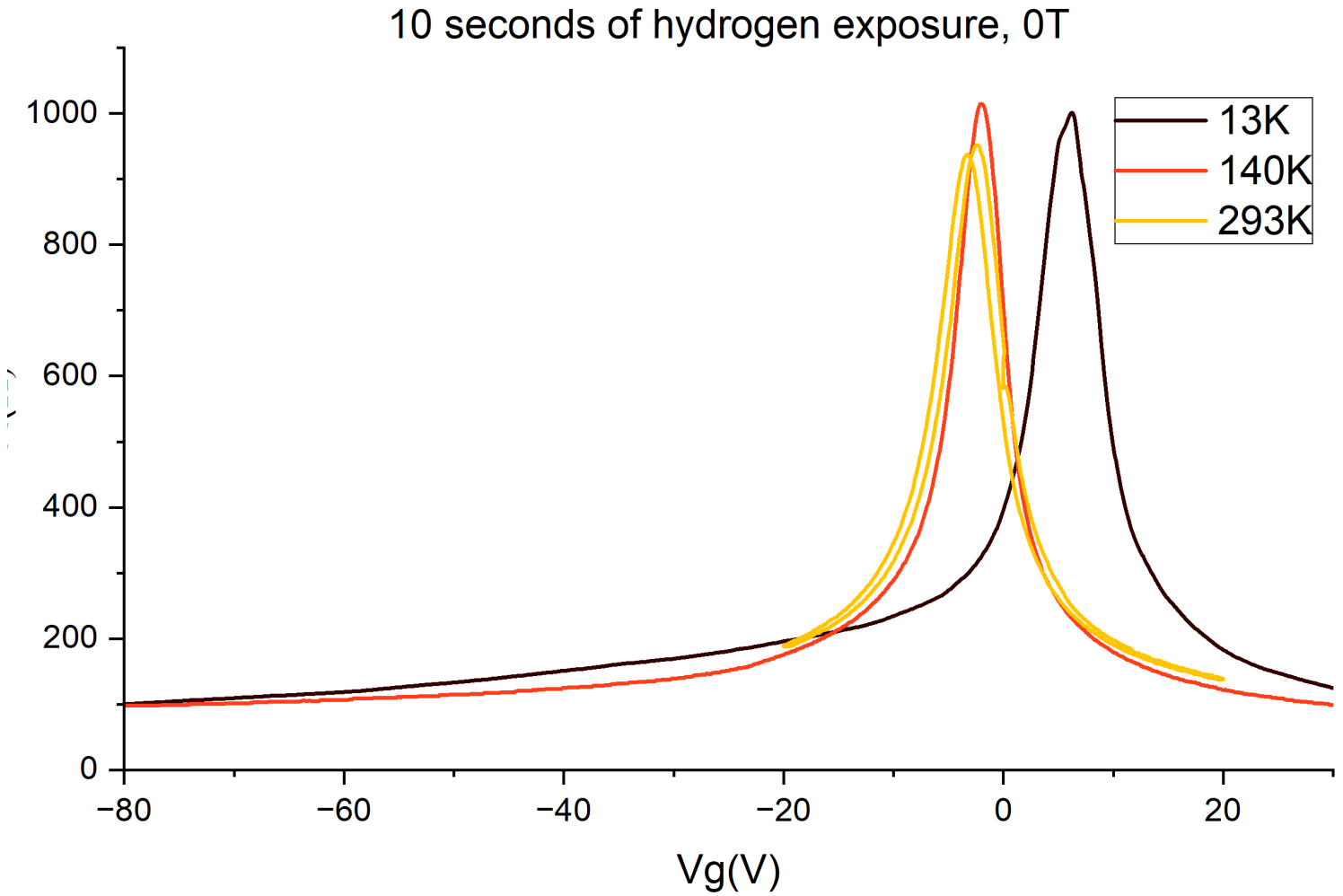
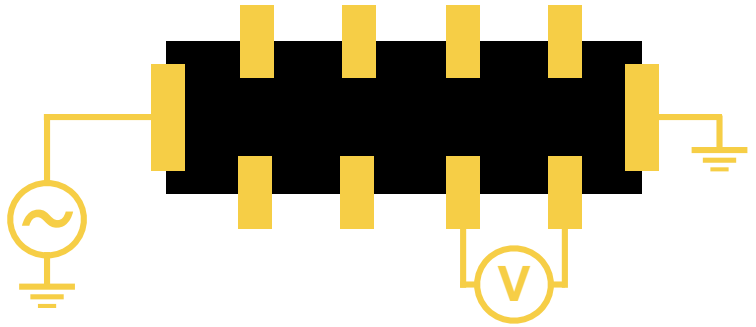
HFML
Science in High Magnetic Fields

Institute for Mathematics, Astrophysics and Particle Physics
Radboud University

Temperature dependence





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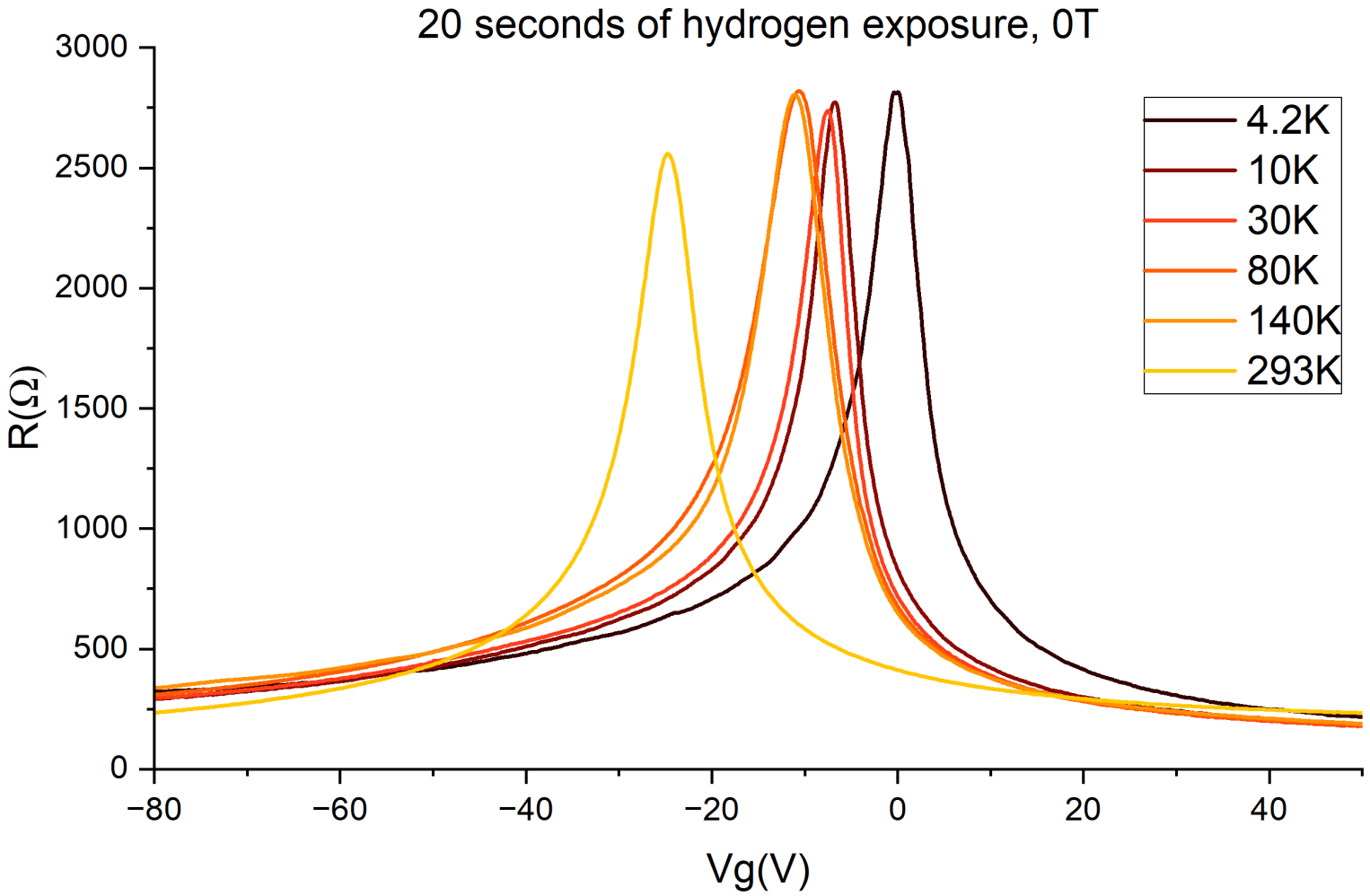
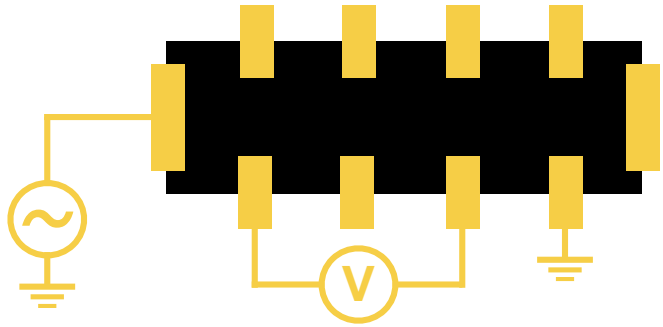
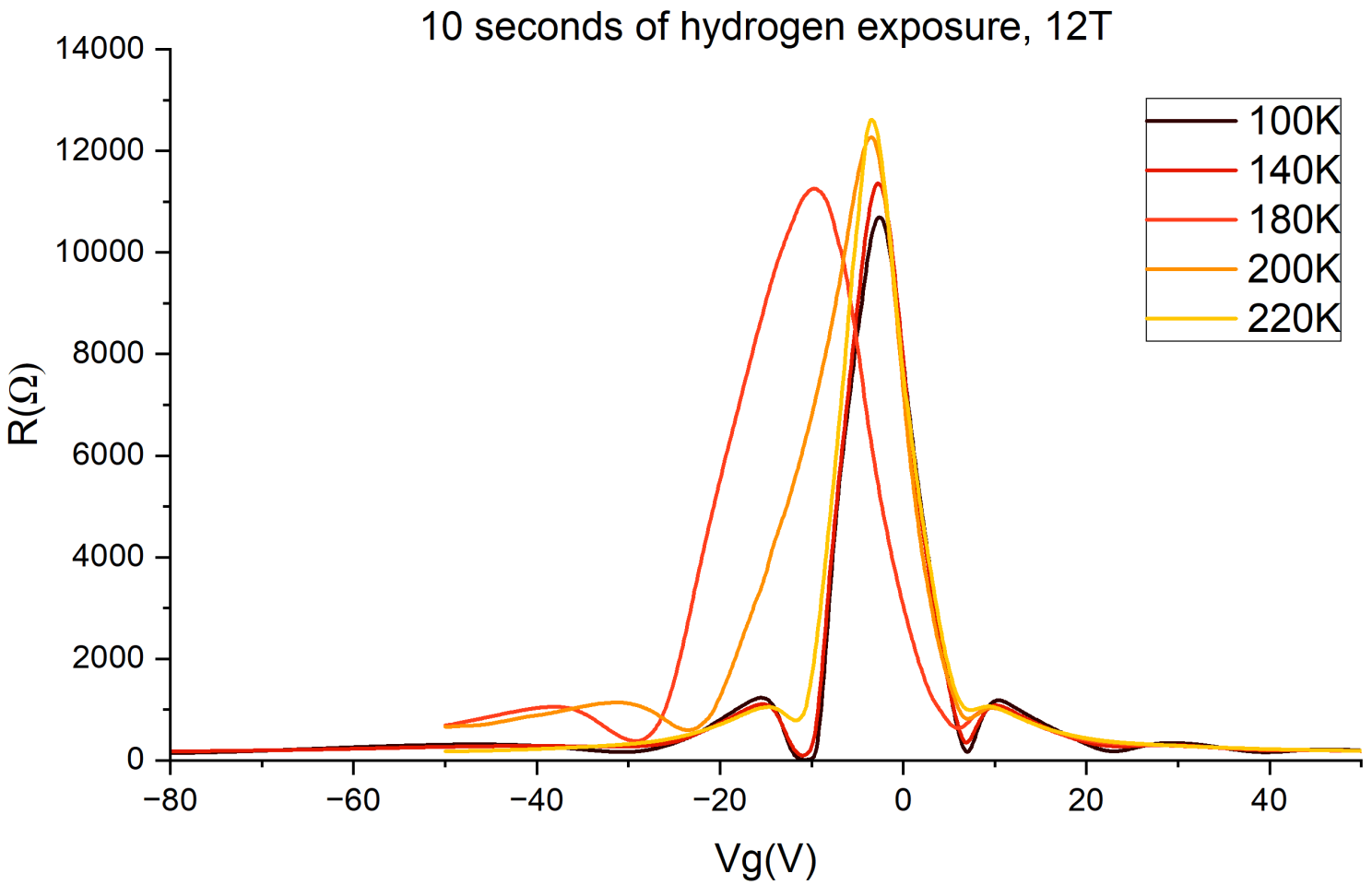
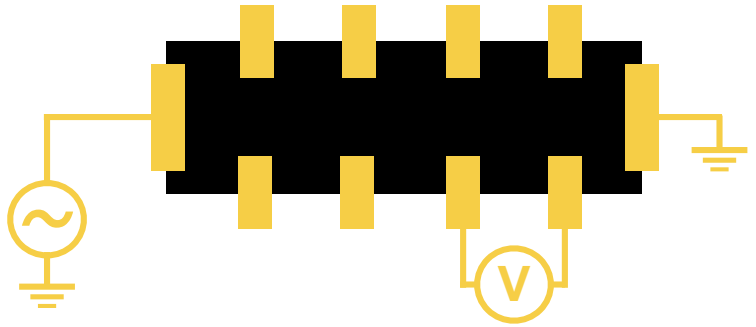




Quantum Hall effect





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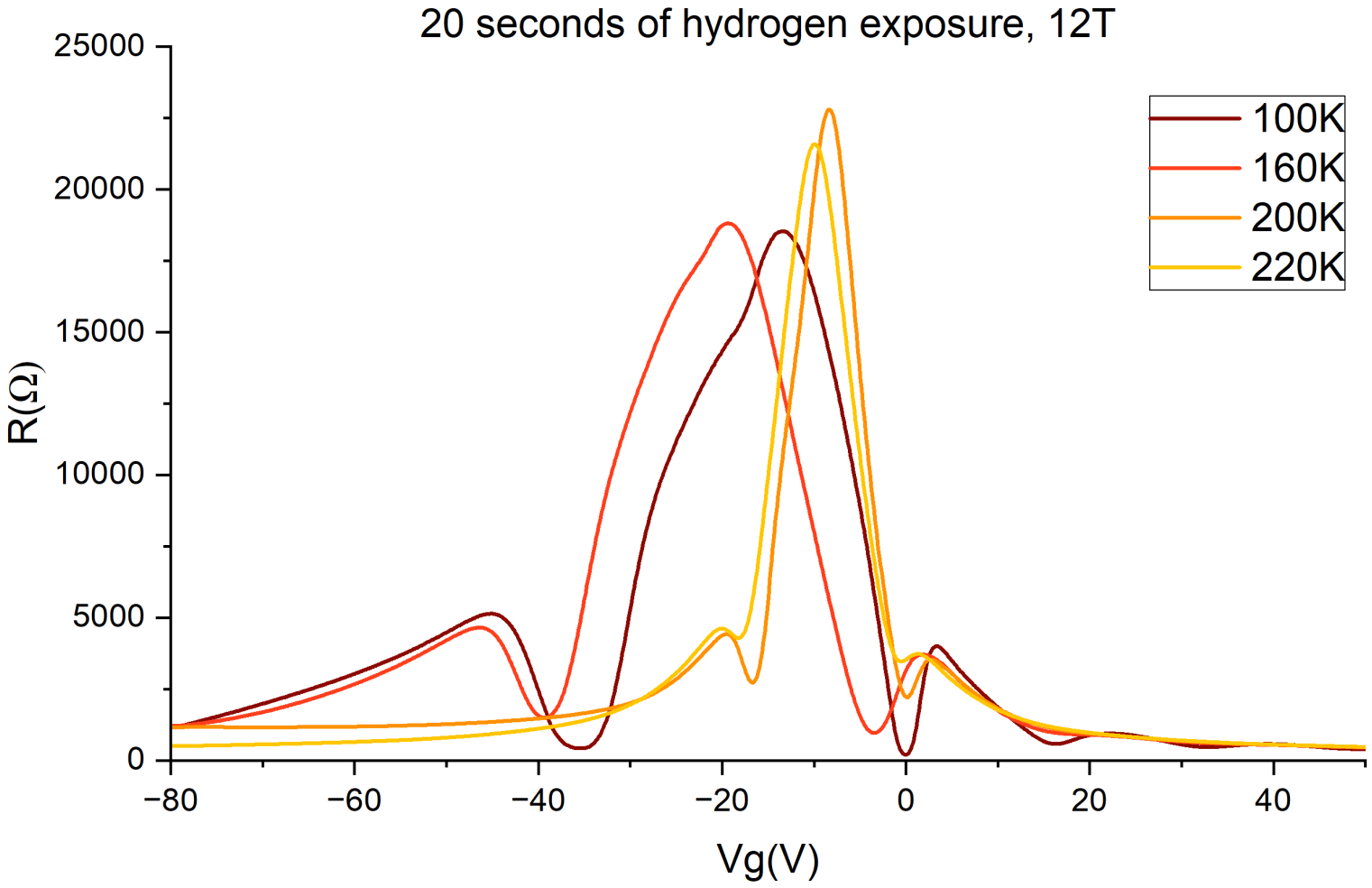
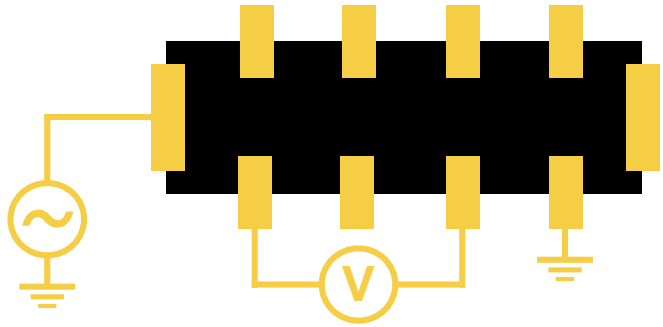
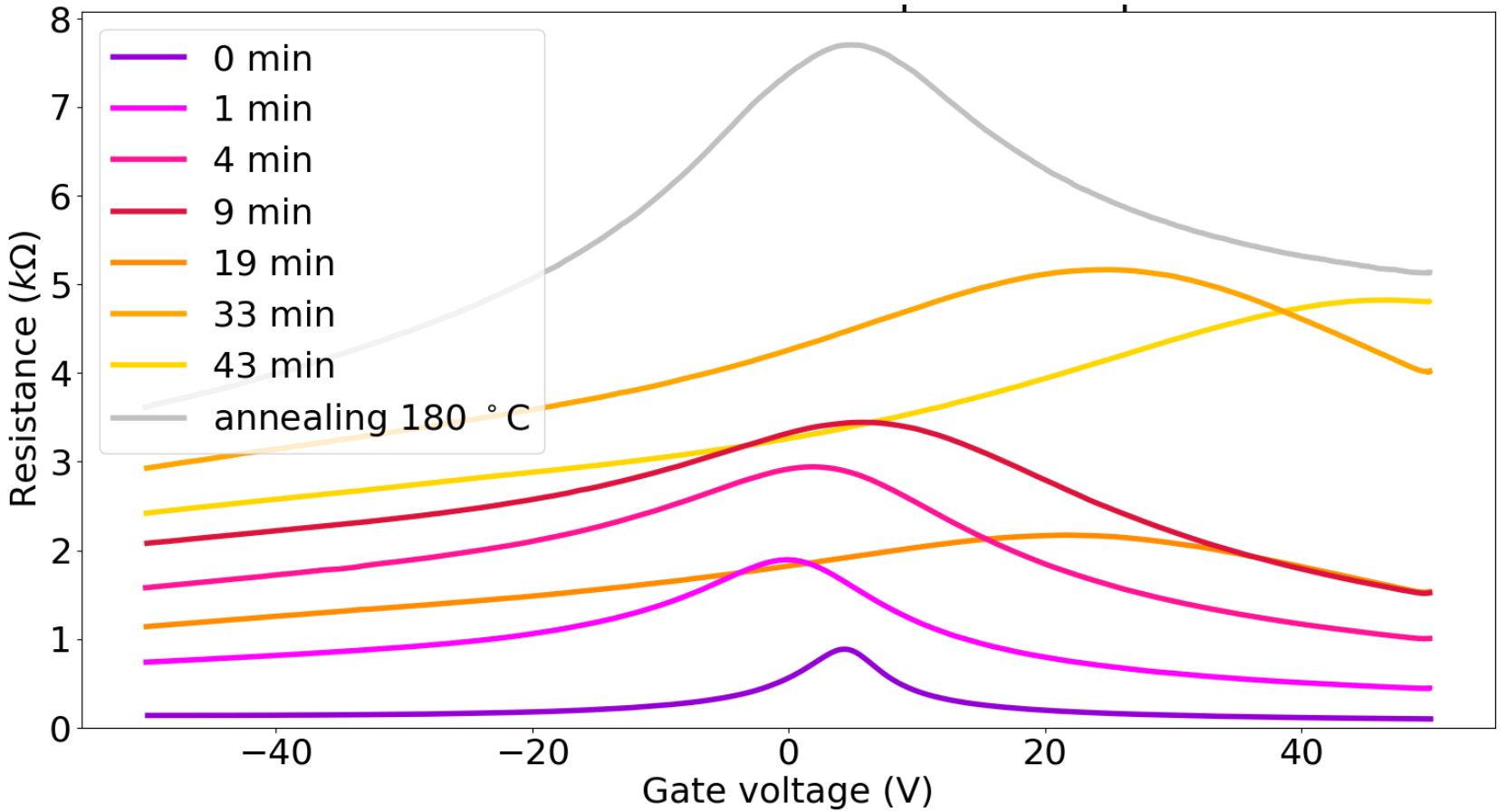
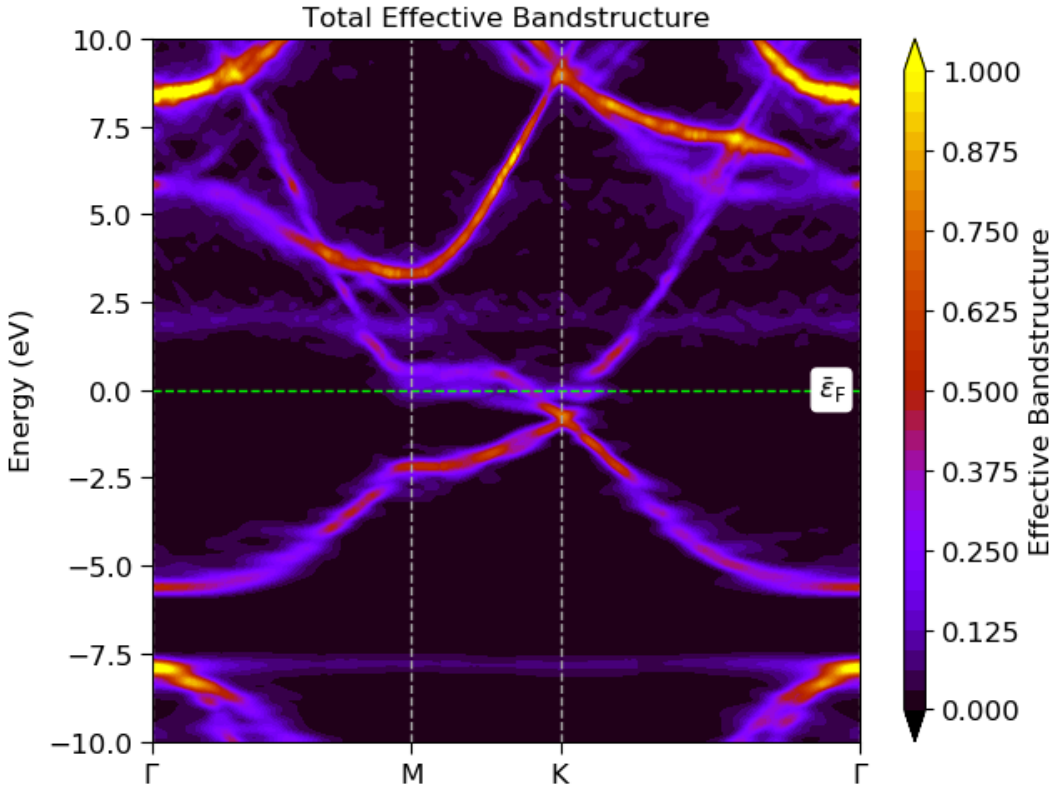


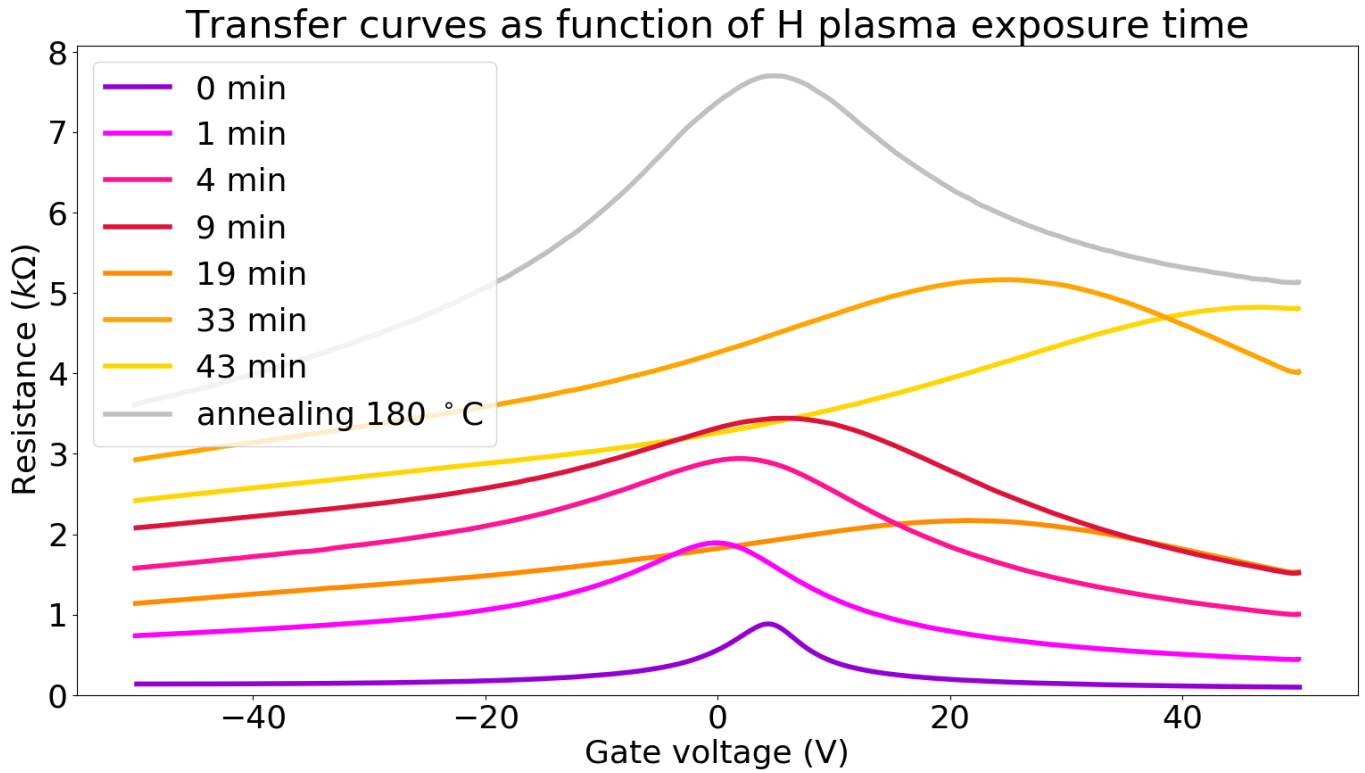


Transfer curves after hydrogenation

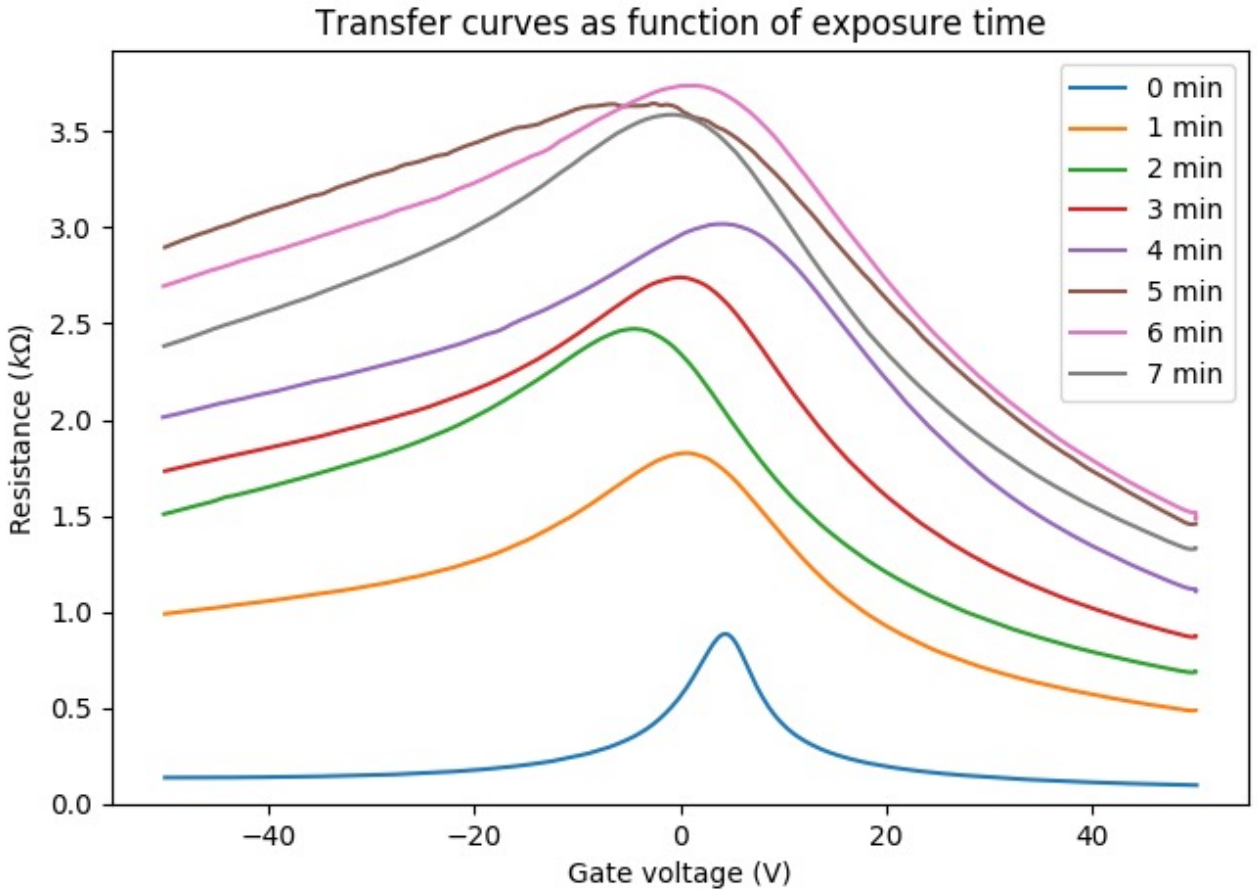


Compare simulations to hydrogenation results

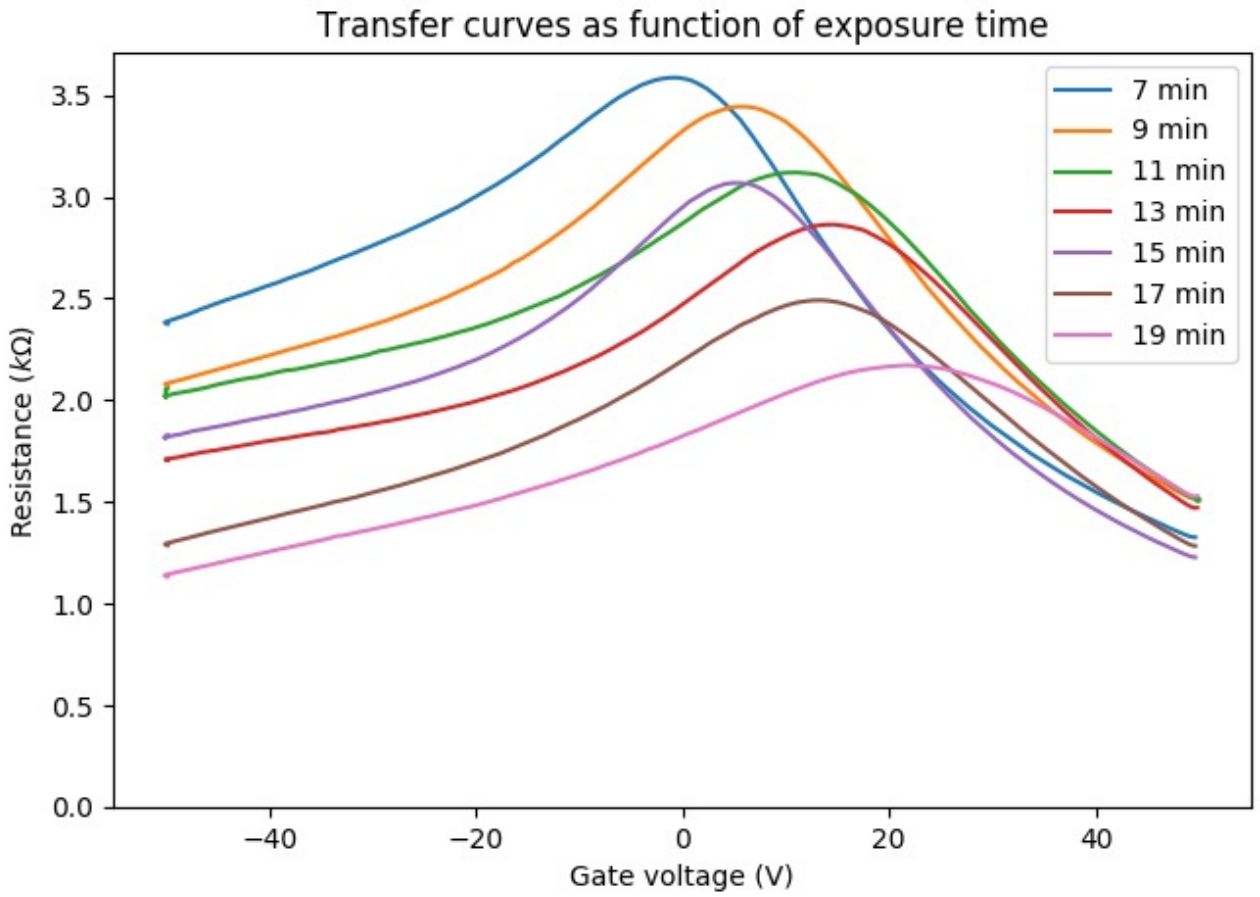




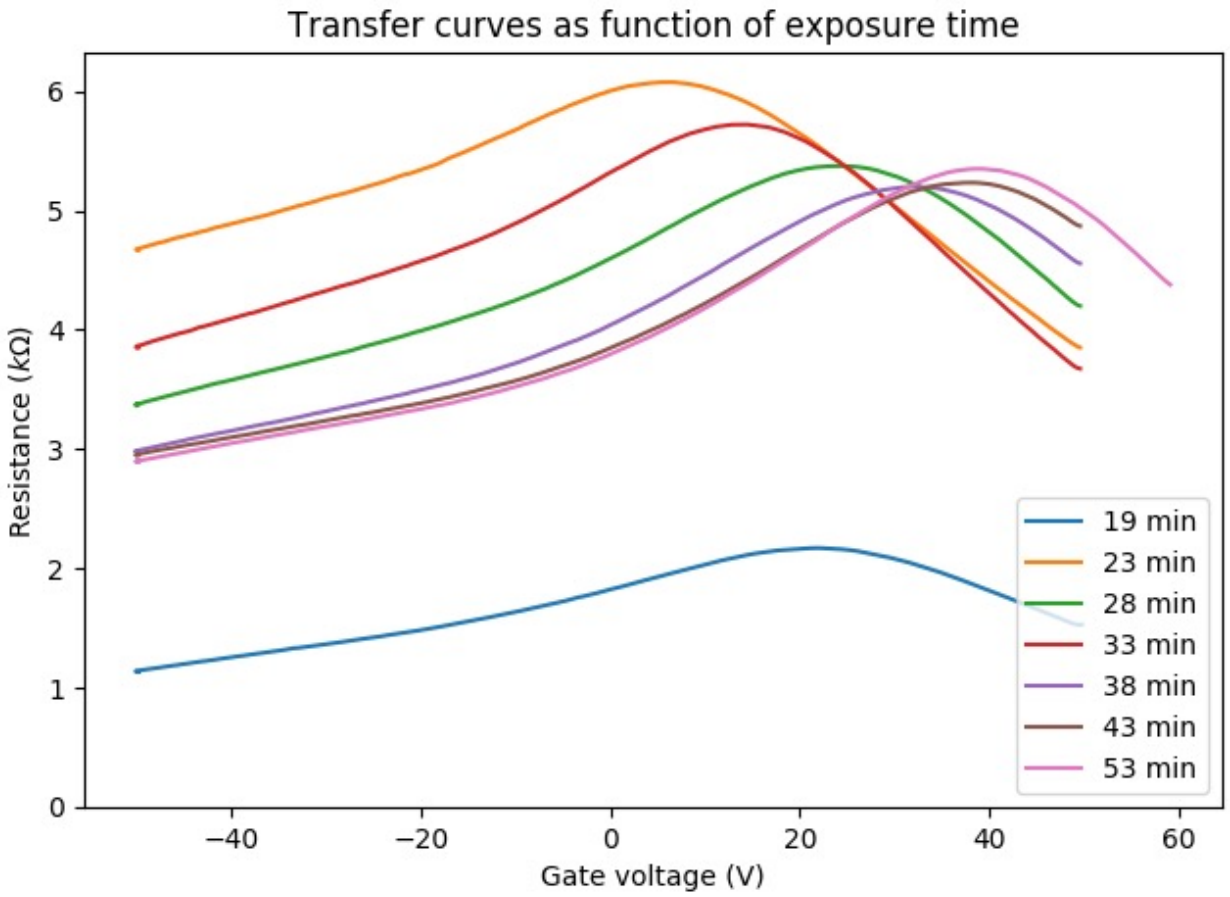
H exposure


Transfer curves as function of exposure time
Resistance (kΩ)
Gate voltage (V)
0 min
1 min
2 min
3 min
4 min
5 min
6 min
7 min
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
−40
−20
0
20
40

H exposure


Transfer curves as function of exposure time
Resistance (kΩ)
Gate voltage (V)
7 min
9 min
11 min
13 min
15 min
17 min
19 min
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−40
−20
0
20
40

H exposure



Hydrogen exposure may increase or decrease resistance