Quantum Resistance Metrology

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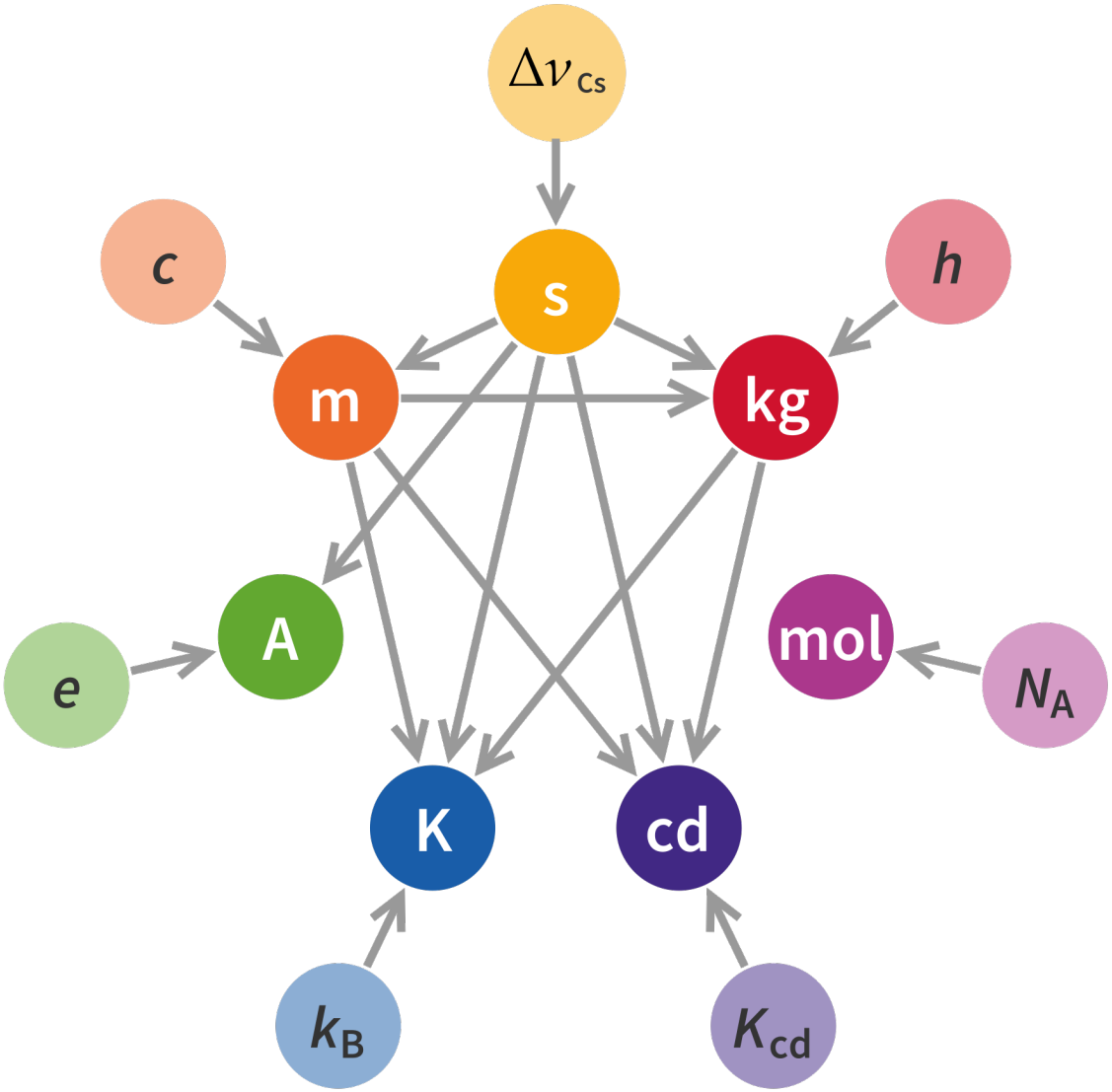
Redefinition of SI in terms of true invariants of nature

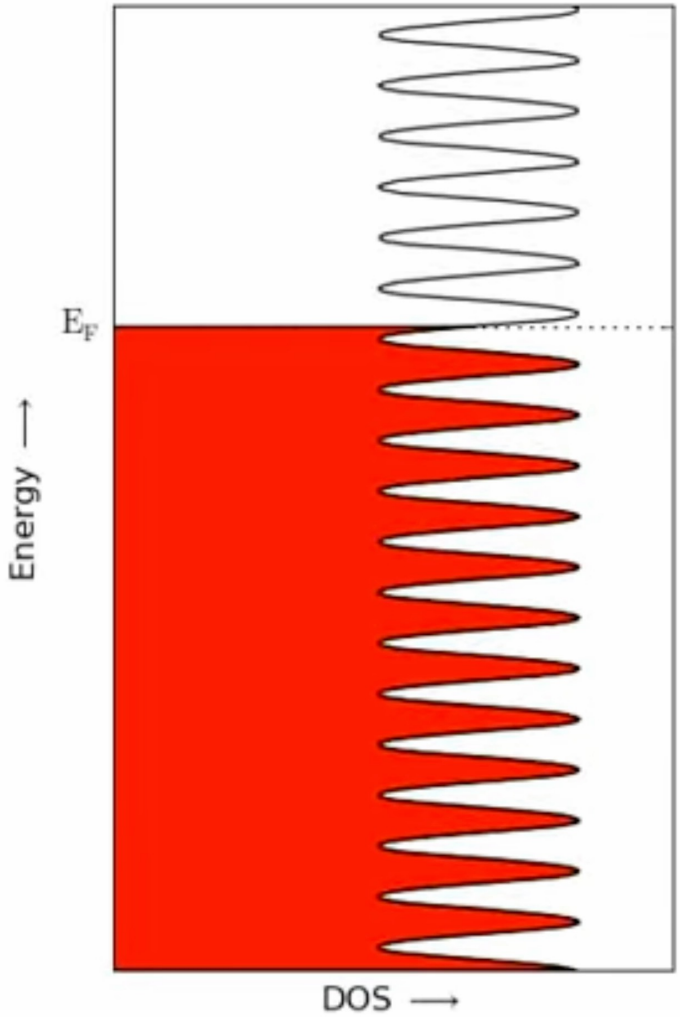
A vote happened on November 16, 2018, at Versailles, France.

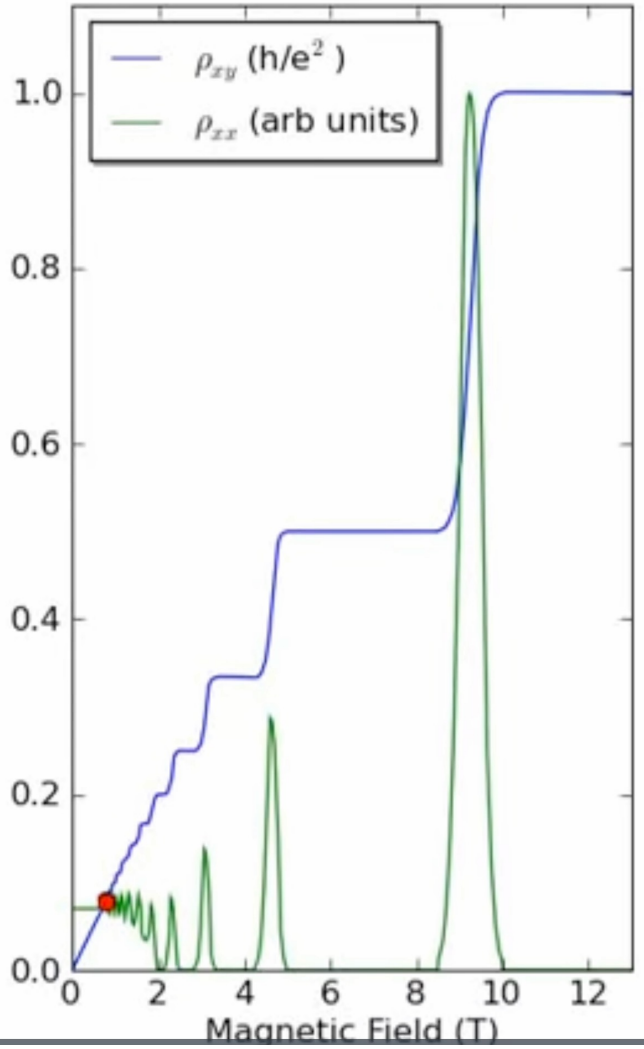
The change went into effect on May 20, 2019.

Redefinition of SI in terms of true invariants of nature



Integer Quantum Hall Effect





Requirements of Resistance Metrology

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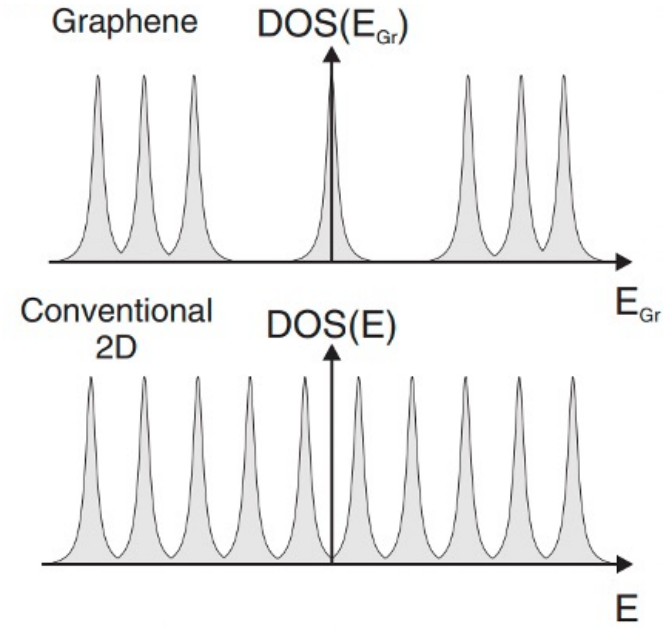
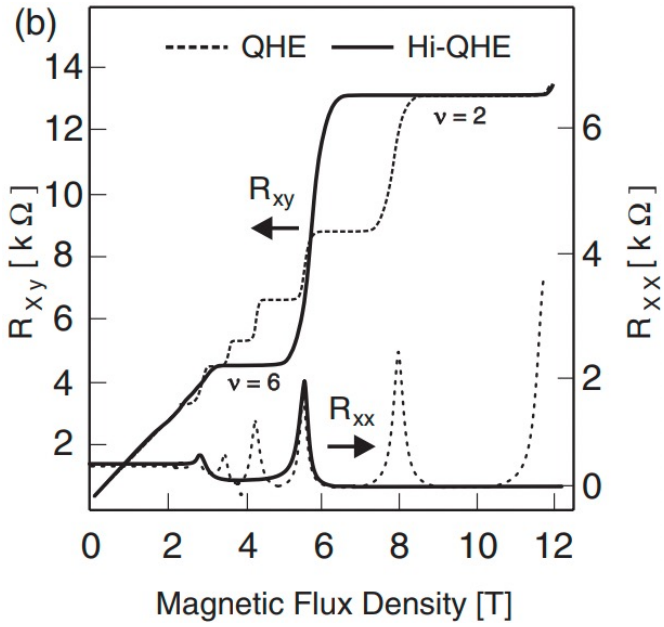
01	02	03
Accuracy	**Reproducibility**	**Uncertainty**
		
$\left(\frac{R_K}{2} - R_{xy}\right) / \left(\frac{R_K}{2}\right)$	$\frac{S}{\overline{R_{xy}}\sqrt{n}}$	$\frac{S}{\overline{R_{xy}}}$
R_K is the von Klitzing constant (h/e²)	S is is the standard deviation, n is the number of all data	$\overline{R_{xy}}$ is the average value of all the data measured

Unique Advantage of Graphene

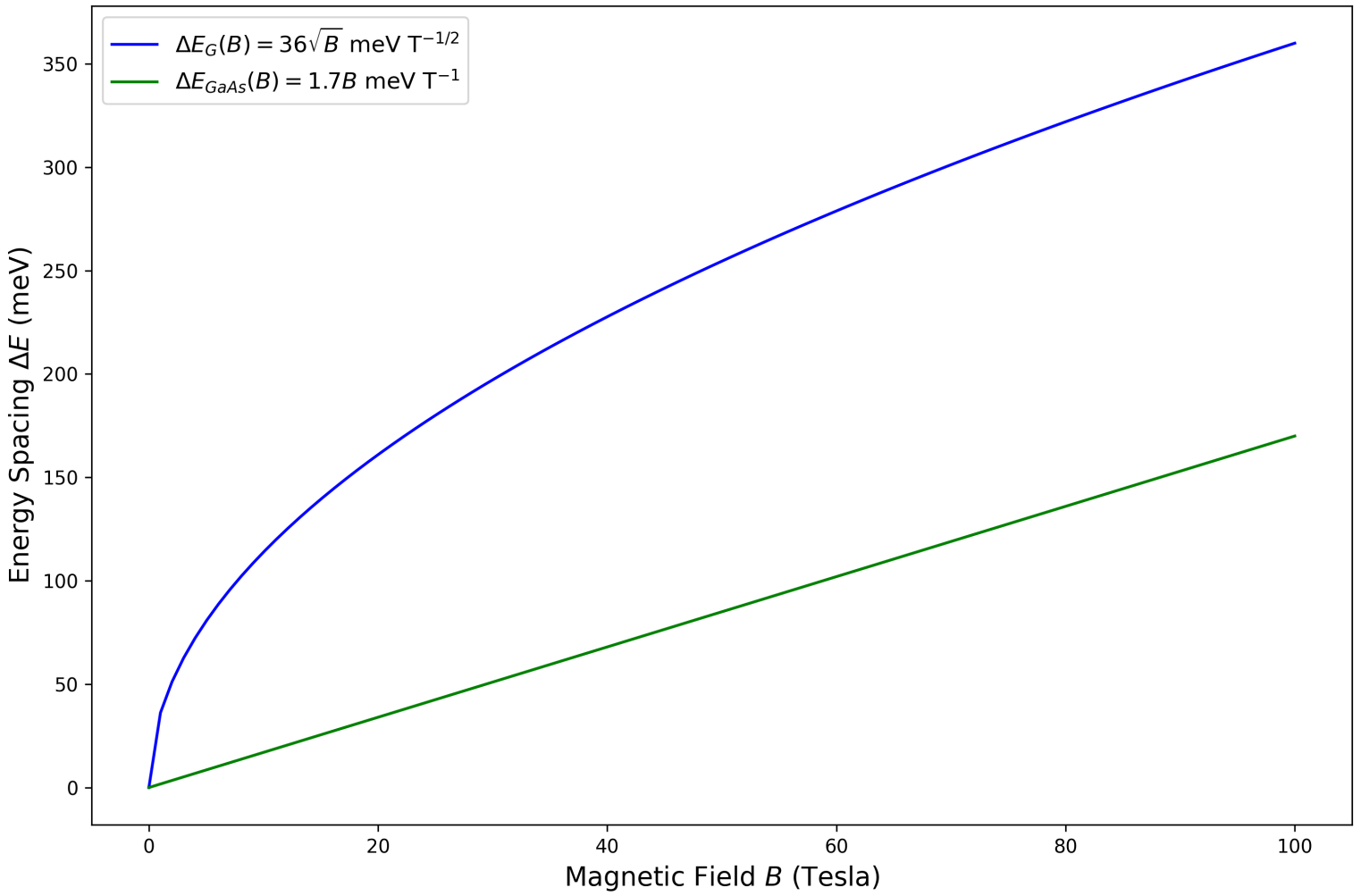
Name	LL Spacing	Degeneracy	Unique N=0
Graphene	$\Delta E_{LL} \propto \sqrt{B}$	Spin and Valley	Half Electron Half Hole
GaAs	$\Delta E_{LL} \propto B$	Spin	None



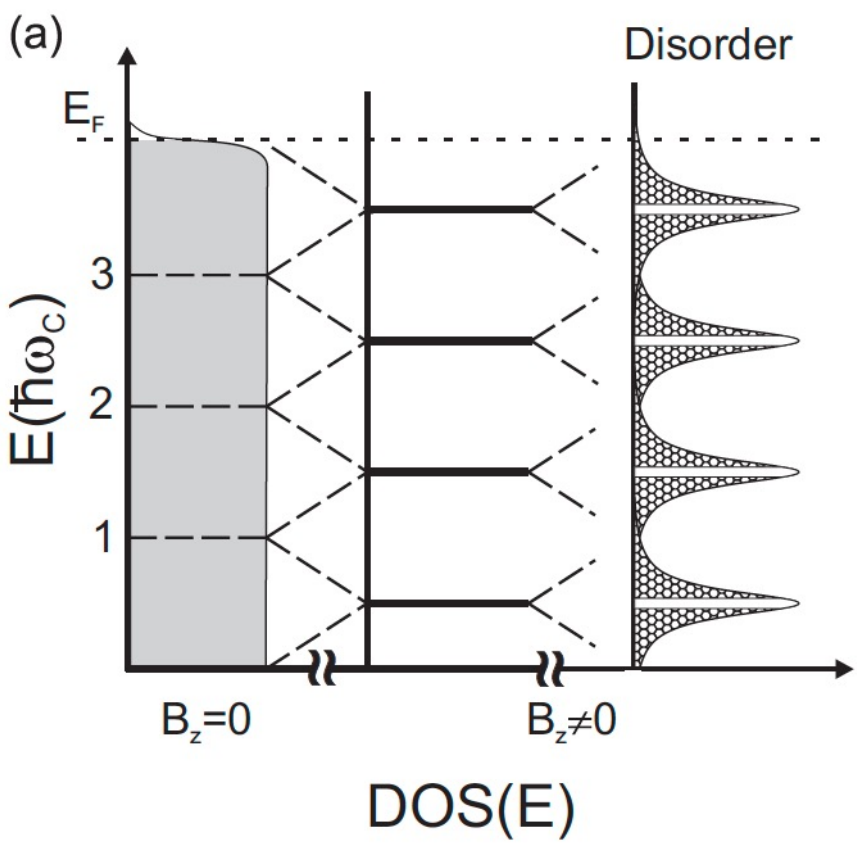


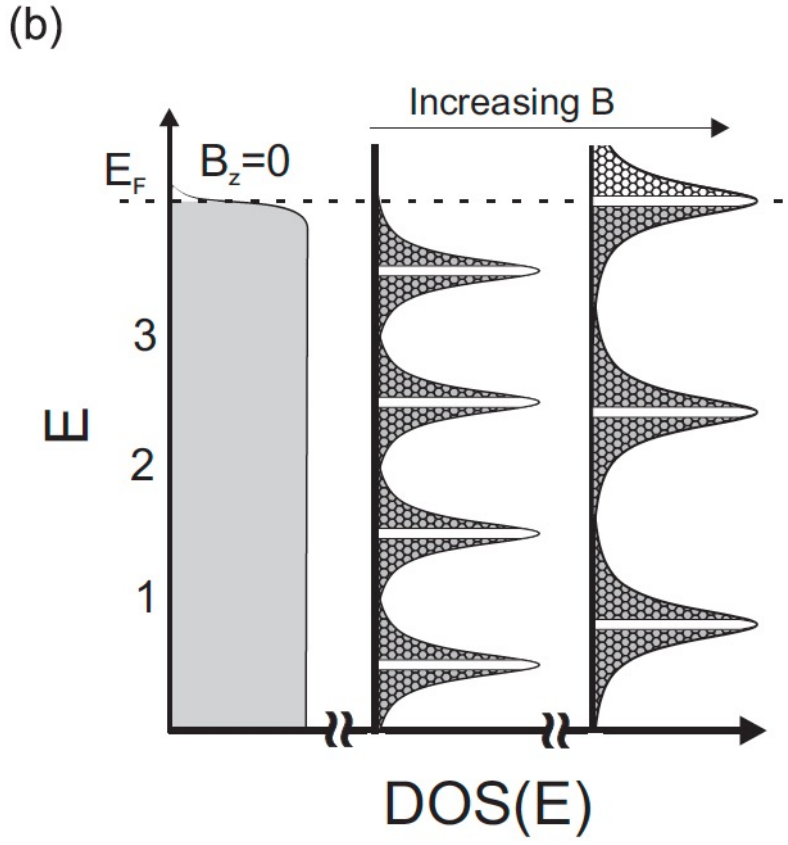
Breakdown field: $E_y = \sqrt{B\hbar\omega_c/e\tau_e}$ 13.6 times better Graphene vs GaAs

LL Spacing


$\Delta E_G(B) = 36\sqrt{B}$ meV T$^{-1/2}$
$\Delta E_{GaAs}(B) = 1.7B$ meV T^{-1}
Energy Spacing ΔE (meV)
0
50
100
150
200
250
300
350
0
20
40
60
80
100
Magnetic Field B (Tesla)

Quantization of cyclotron motion leads to formation of LLs in the DOS

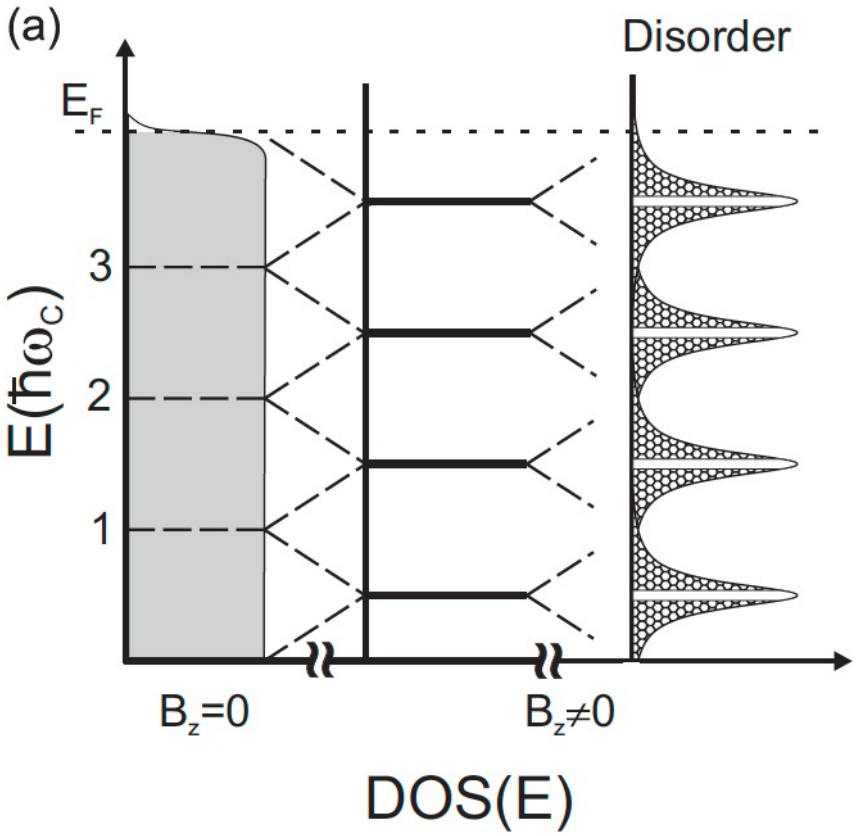


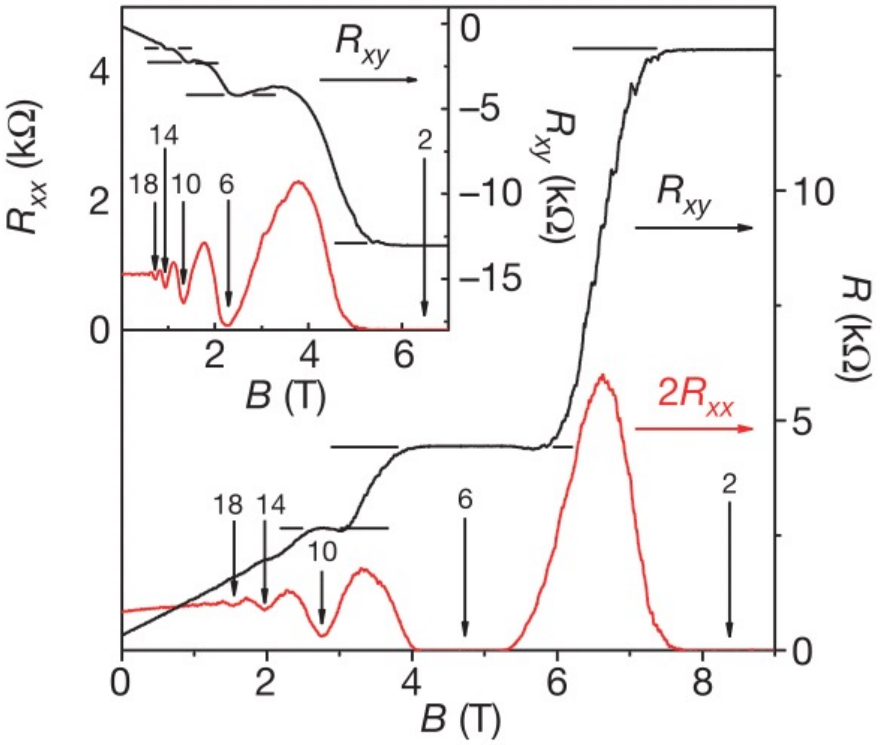


Varying E_F

Varying B

Mobility and Disorder

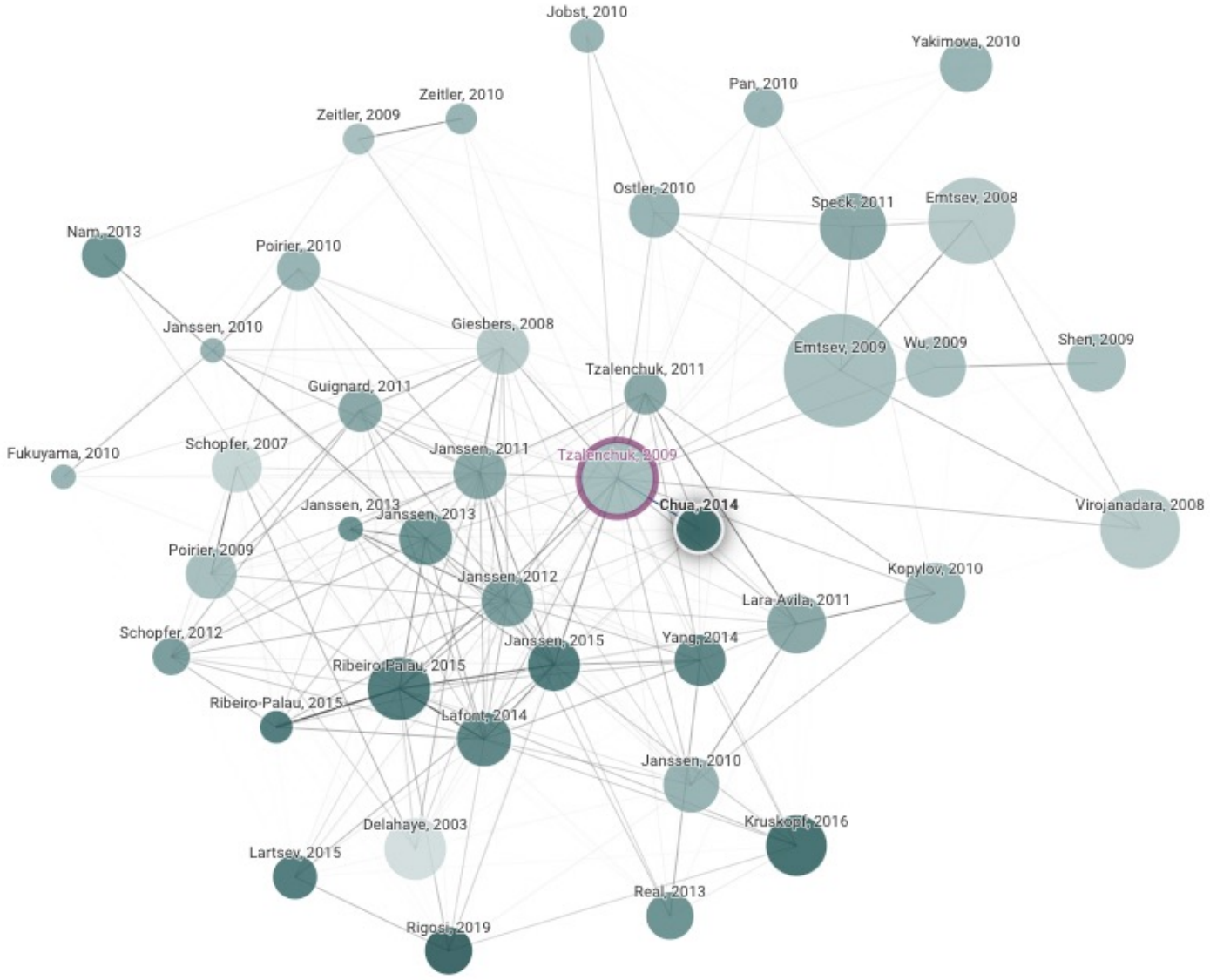




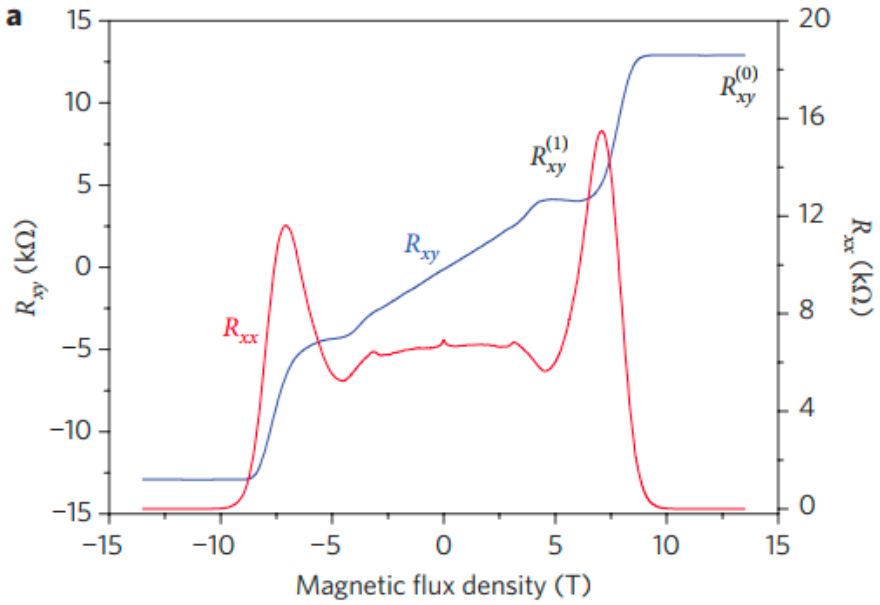
Nature 438.7065 (2005): 201-204

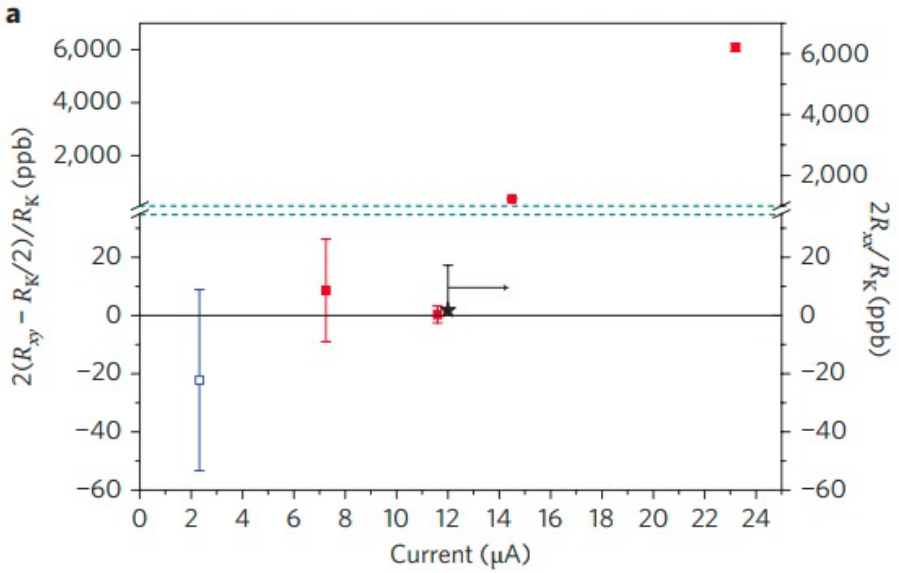
Disorder will broaden Landau levels (LL) and introduce scattering, which will reduce mobility!

Citation Network



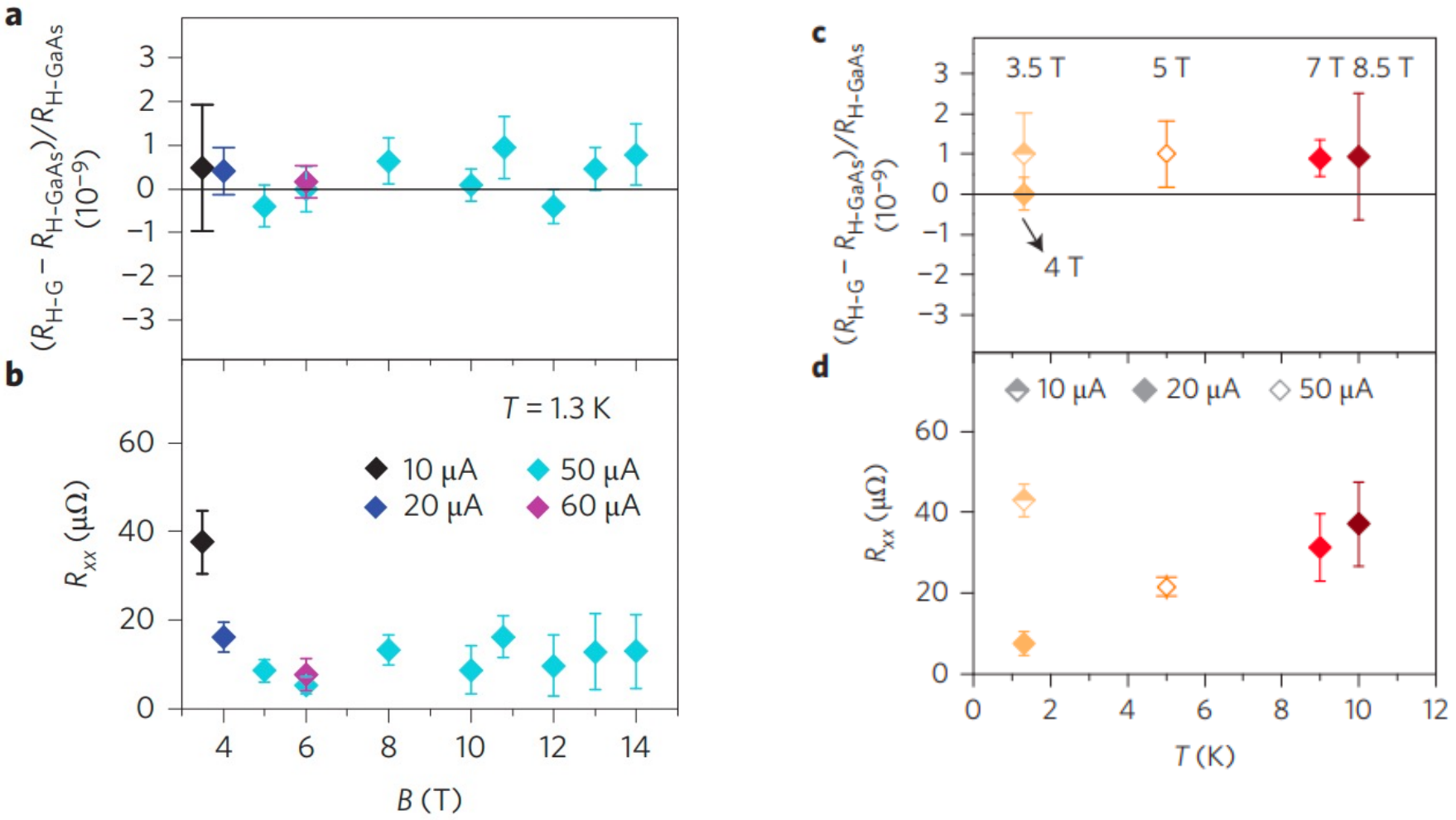
MileStone 1





was achieved by Janssen and colleagues[26–28], who demonstrated excellent R_H accuracy to within 8.7×10^{-11} in epitaxial monolayer graphene grown by silicon sublimation from SiC by measurements mainly at $B = 14$ T and $T = 0.3$ K. However, these operational

MileStone 2

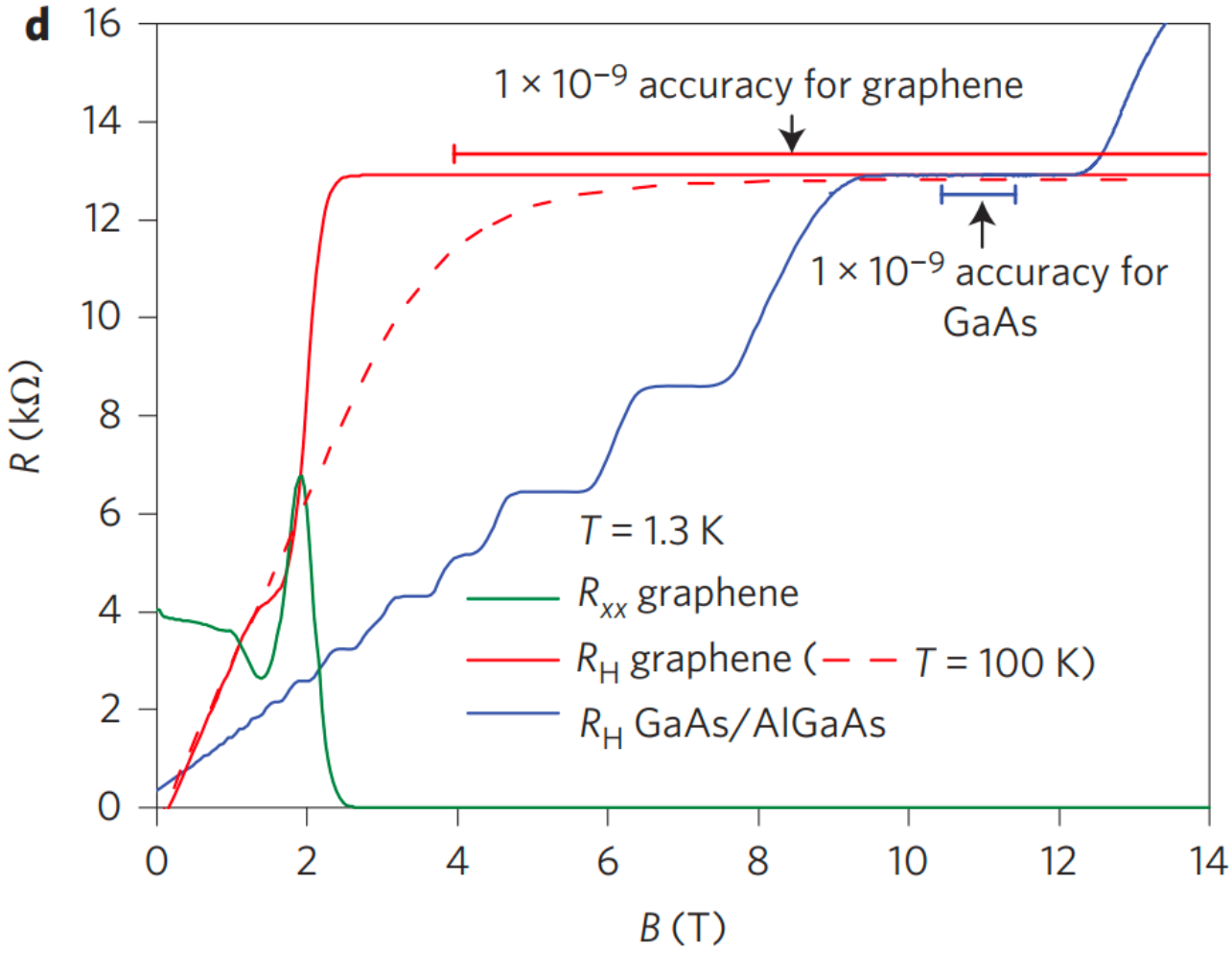


Accuracy: 10^{-9}

Uncertainty: 8.2×10^{-11}

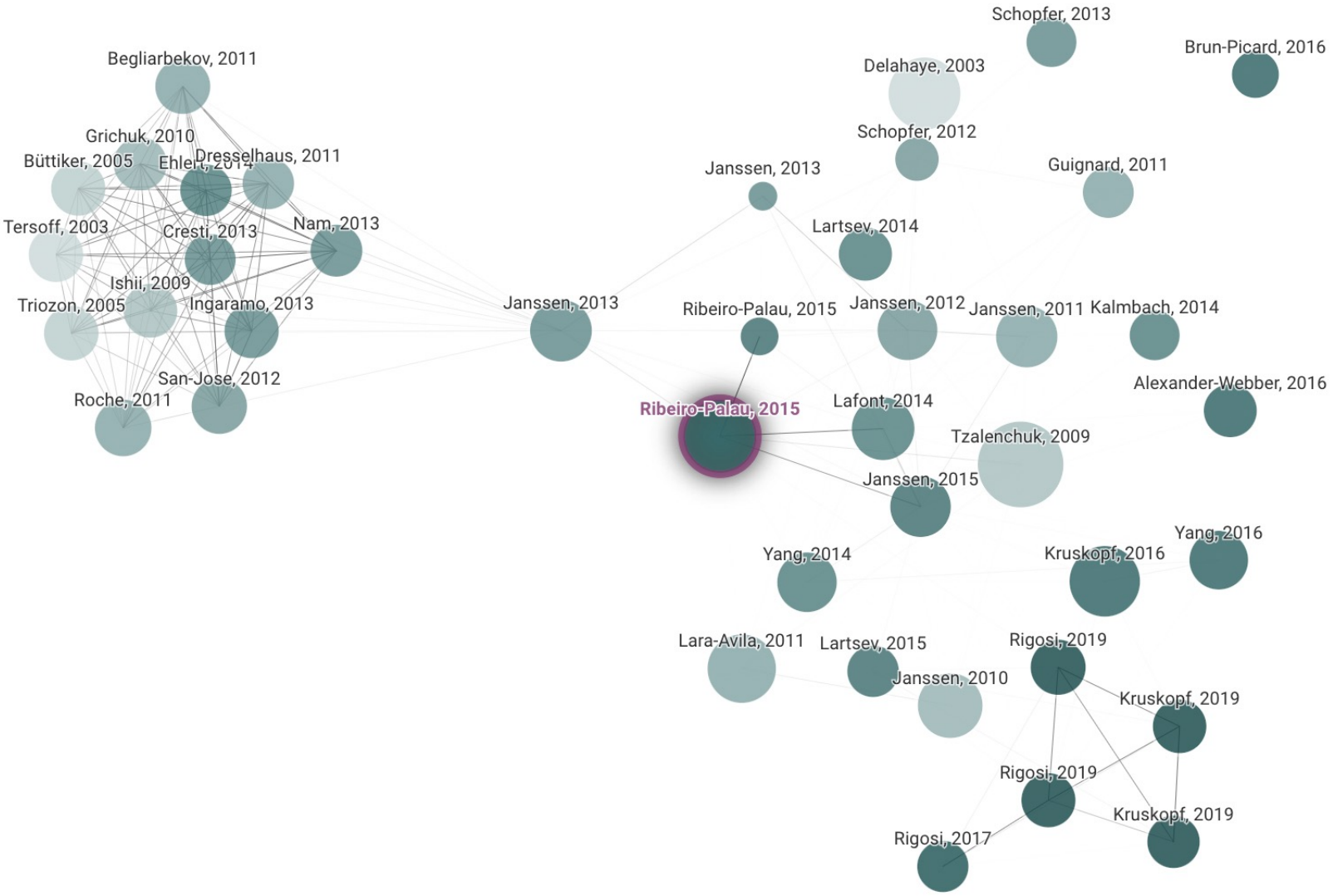
Nature Nanotechnology 10.11 (2015): 965-971

State-of-the-art Graphene Resistance Metrology (GSM)



Nature Nanotechnology 10.11 (2015): 965-971

Citation Network



Graphene Fabrication Method

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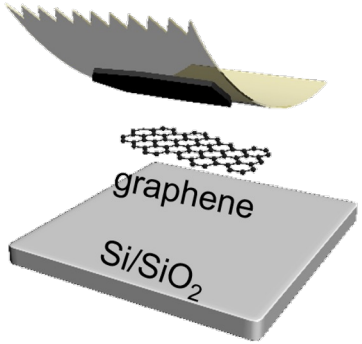
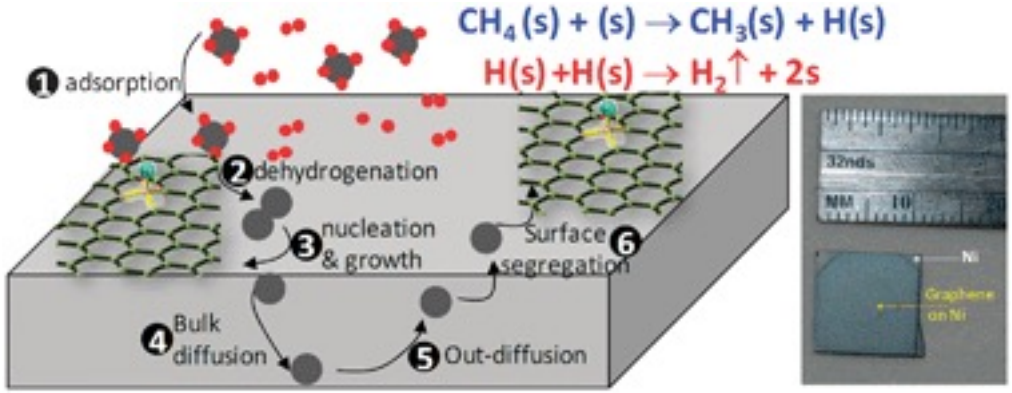
Exfoliation

First Devices

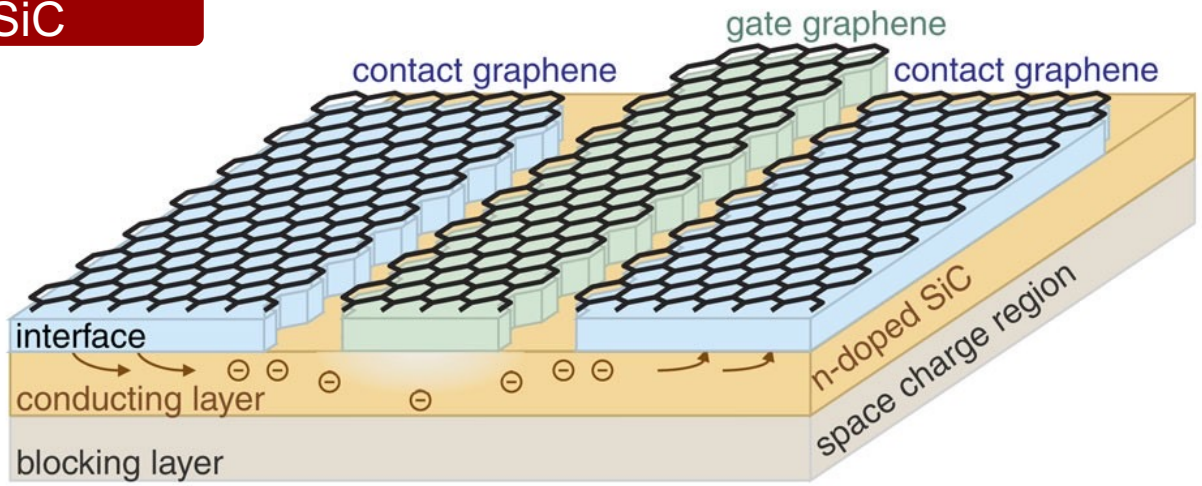
Exfoliation to Si/SiO_2



CVD

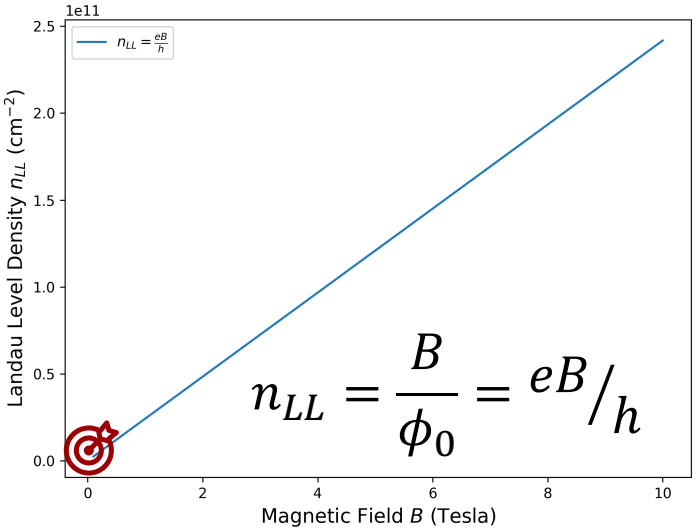


SiC

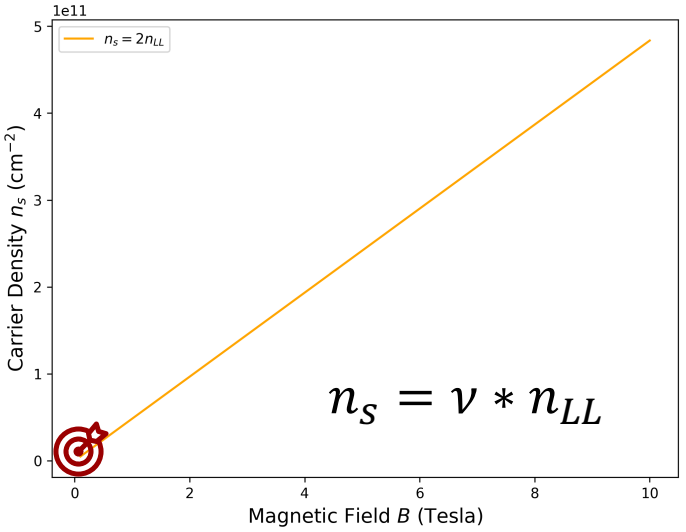


Challenges of Current Graphene Resistance Metrology

Name	Area	Doping (cm^{-2})	Mobility (cm^2/Vs)
SiC Gr	Large	10^{12}–10^{13}	<10000
CVD Gr	Large	>10^{12}	<10000
Exfo Gr	Small	~10^{9}	>100000



ν=2



$\omega_c^{-1} \ll \tau$ → $B \gg \mu^{-1}$

Requirement of Graphene Resistance Metrology (GSM)

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Target

A feasible magnetic field

A low carrier density

→ ν=2 plateau E_F in-between N=0 and N=1 LL

FOM

High breakdown current

Small contact resistances

→ Large Area Graphene

→ High Doping

Maintain a high doping profile in the contact area while keeping a low-level doping inside the channel!

Challenge of GSM

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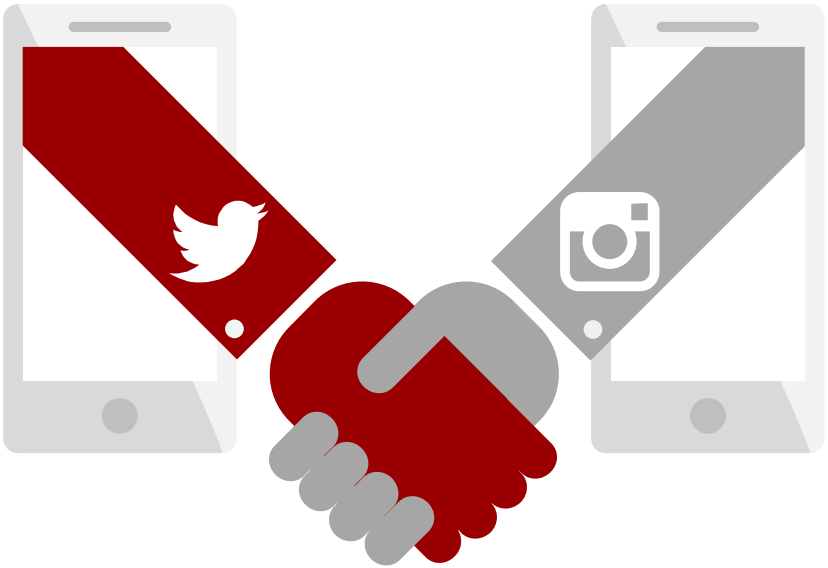
Disorder Reduction

Extrinsic Disorder inside:

Substrate

Buffer-layer

Interface



Doping Control

Doping control within:

Channel

Contacts

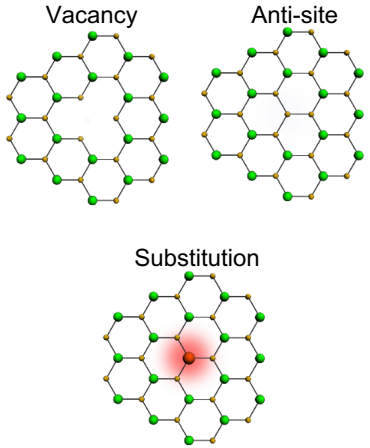
Transition region

Interface control

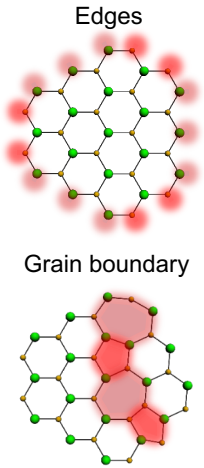
Breakdown field: $E_y = \sqrt{B\hbar\omega_c/e\tau_e}$ 13.6 times better Graphene vs GaAs

Disorder Reduction – Research Basis

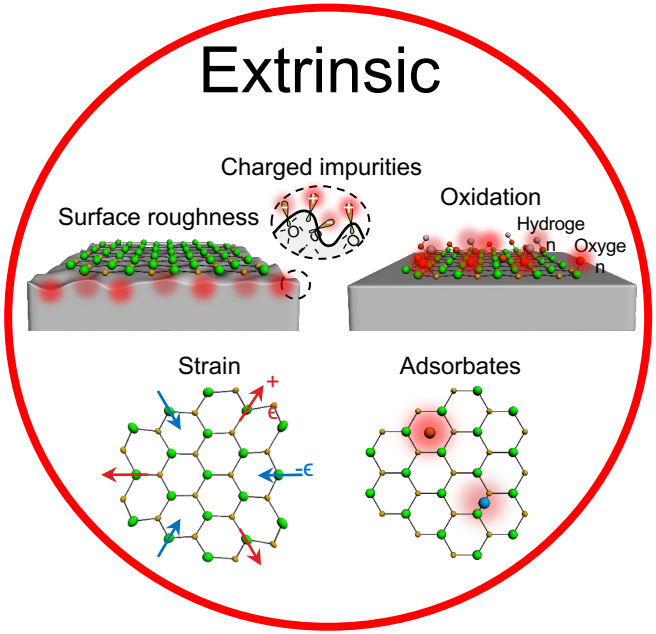
Point Defects



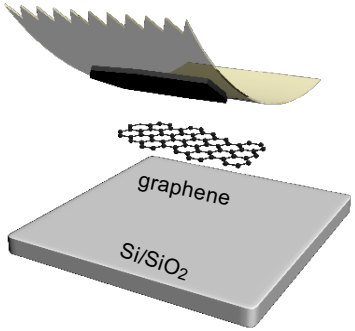
Termination



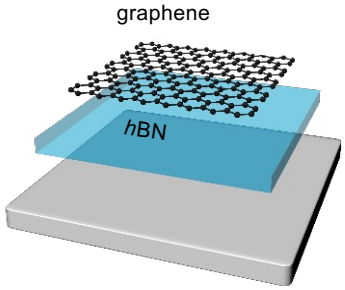
Extrinsic



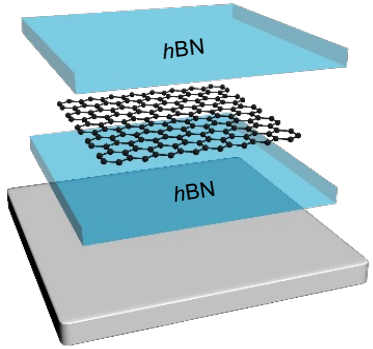
Gen 1
Exfoliation to Si/SiO_2



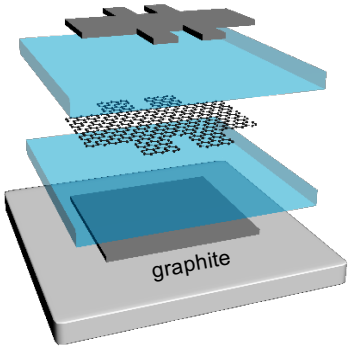
Gen 2
Polymer transfer to *h*BN



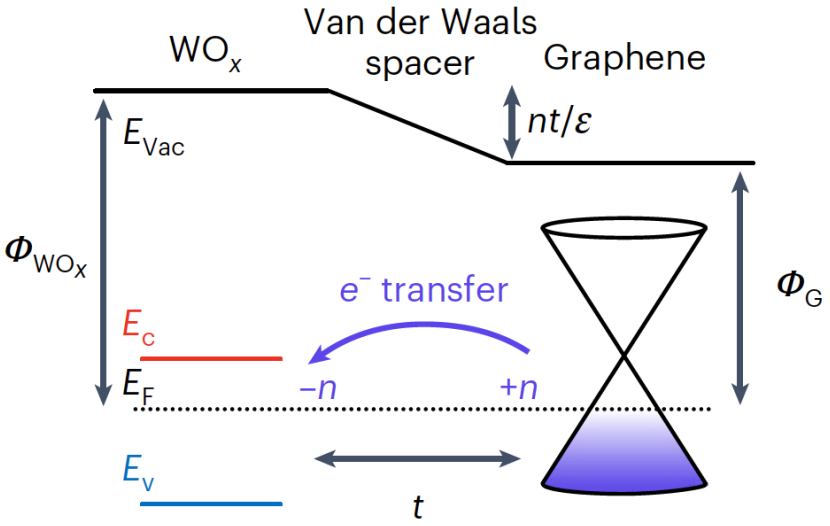
Gen 3
Dry encapsulation

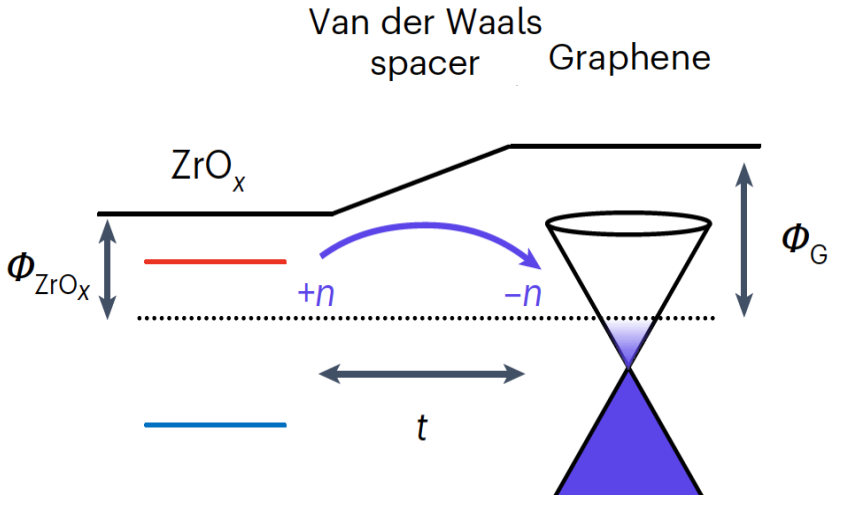


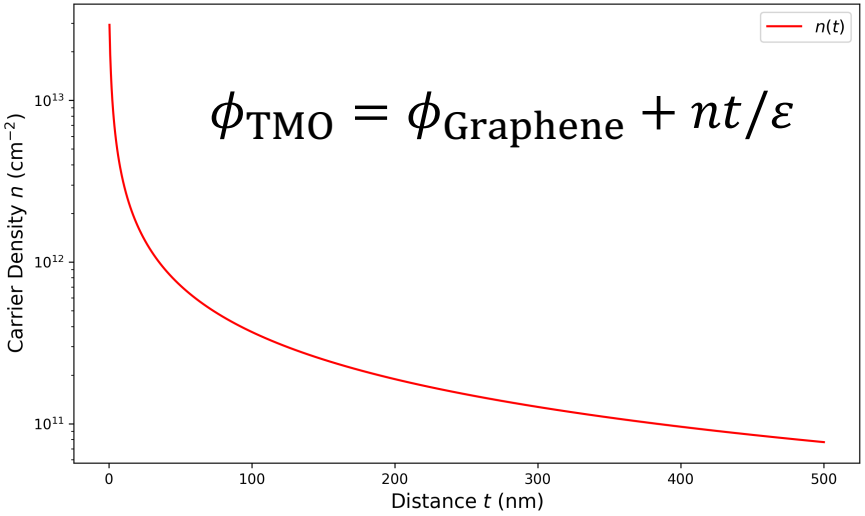
Gen 4
Graphite gating

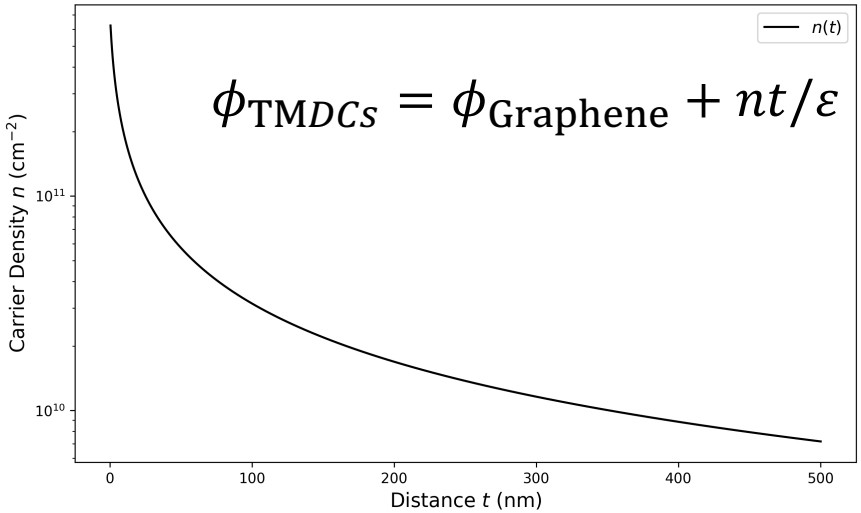


Doping Control – Research Basis

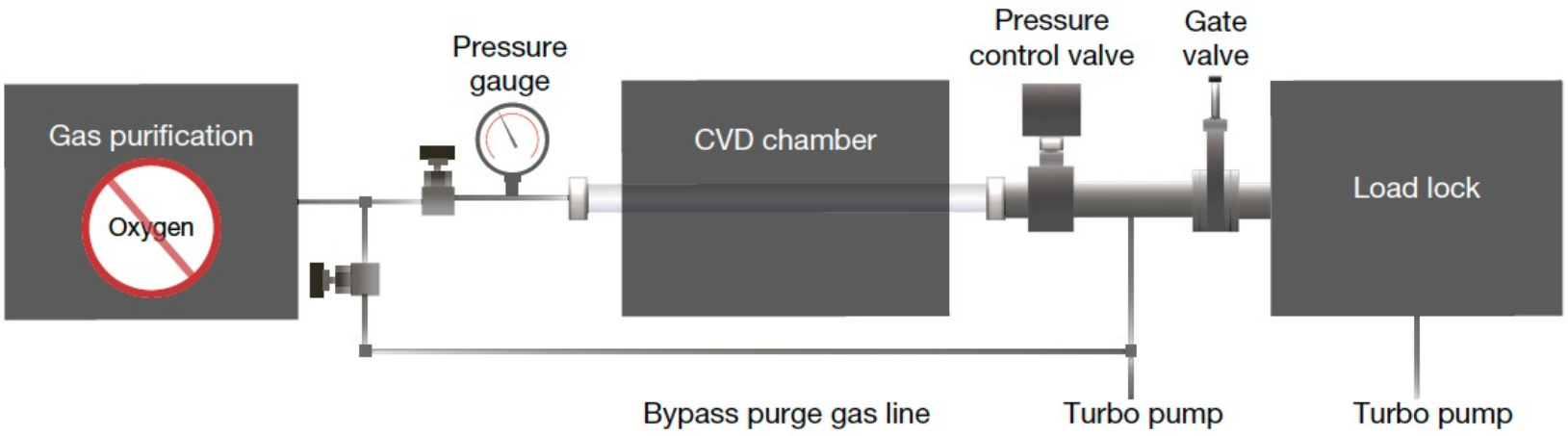


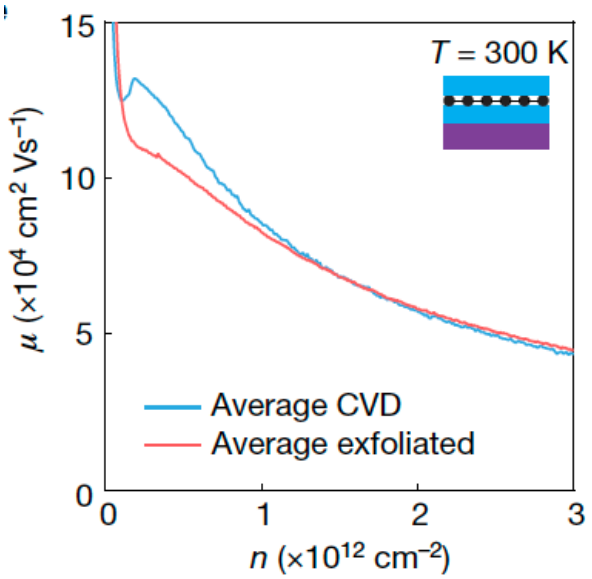


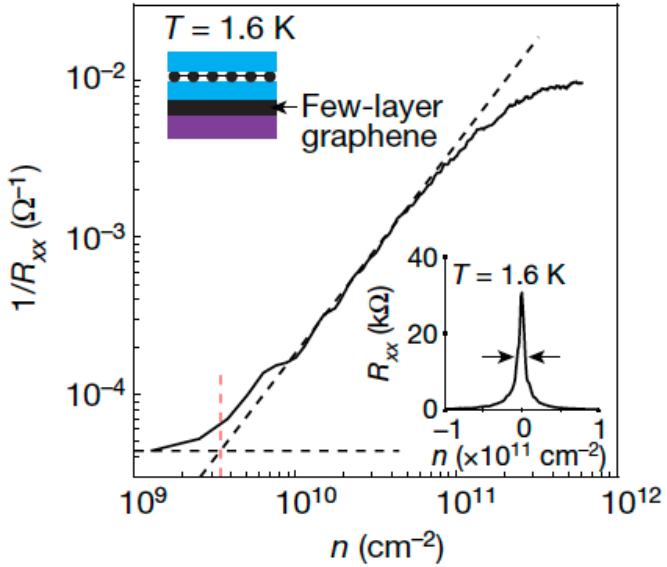




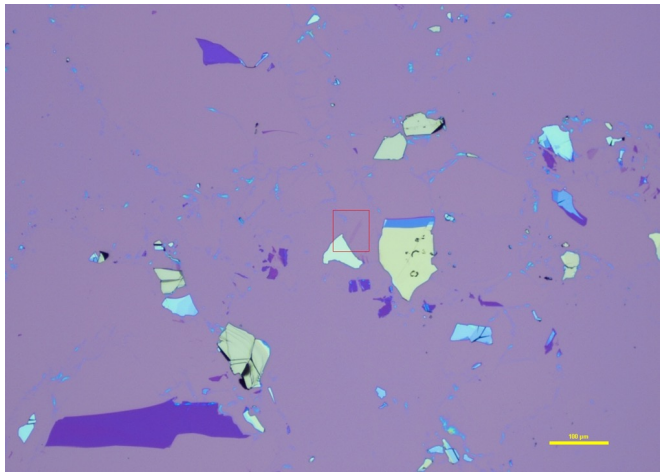
Interface Control – Research Basis of Raw Materials

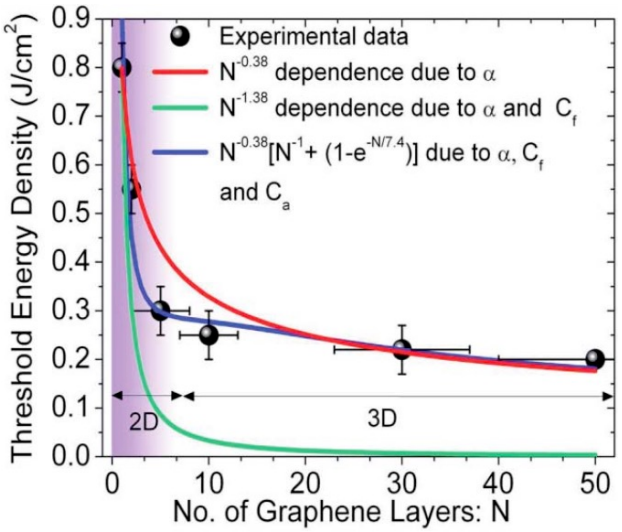


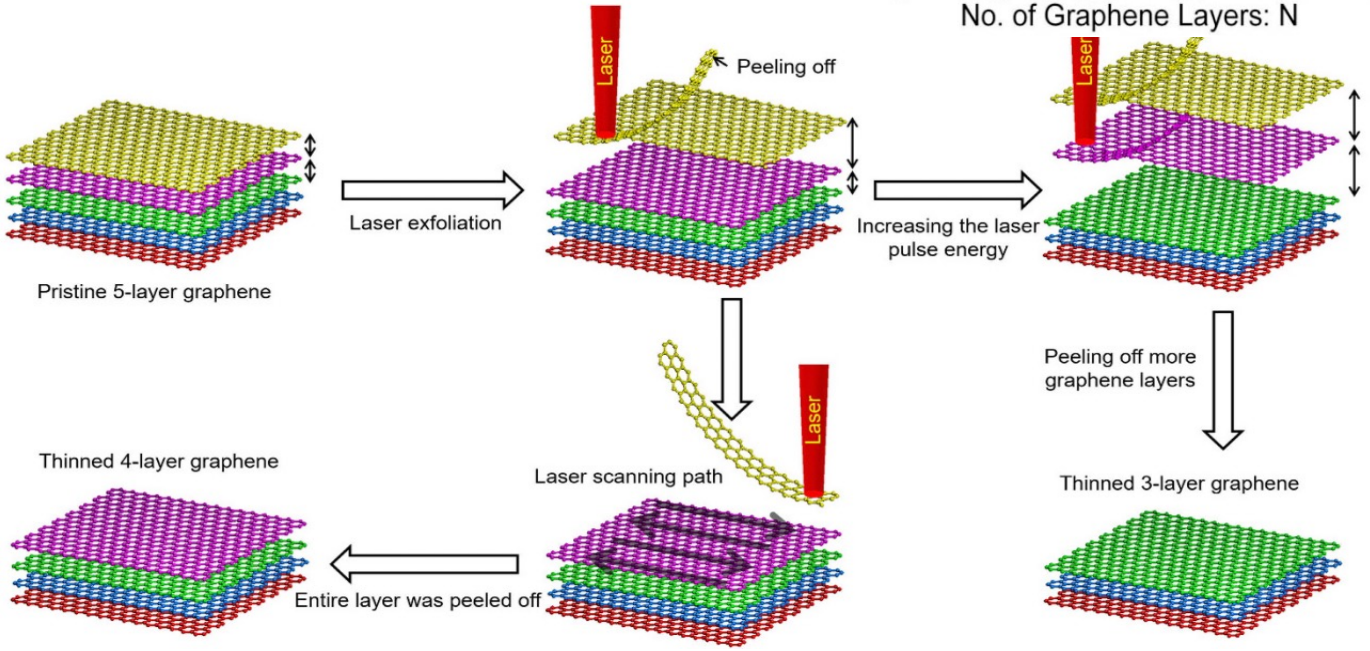




Interface Control – Research Basis of Raw Materials



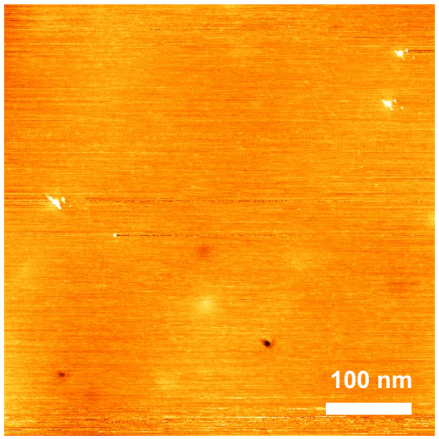




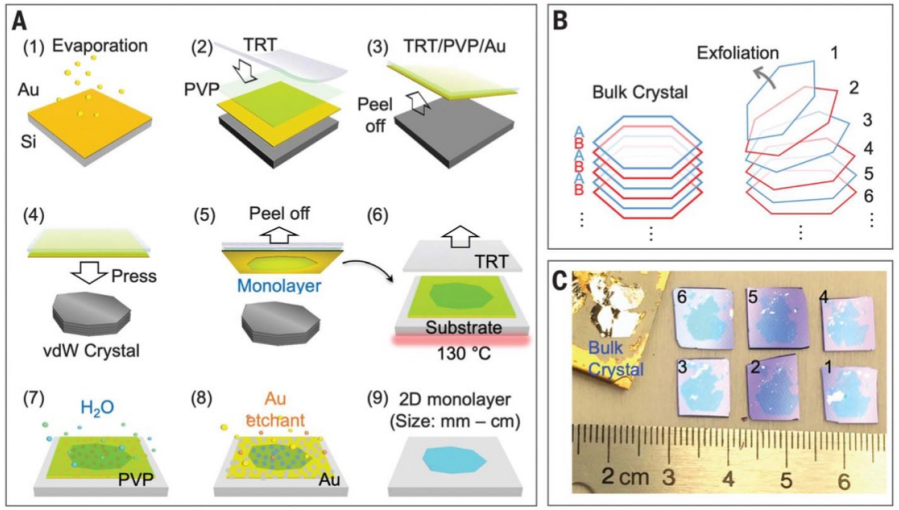
Scientific reports 5.1 (2015): 11662

AIP Advances 1, 022109 (2011)

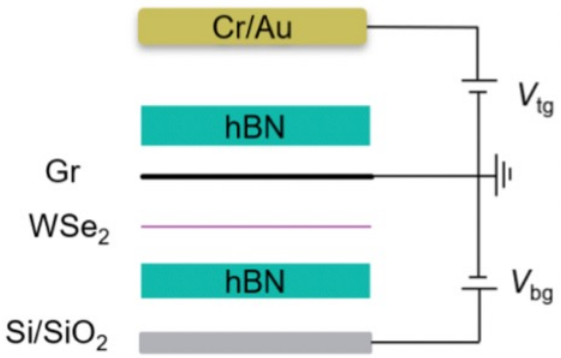
Interface Control – Research Basis of Raw Materials

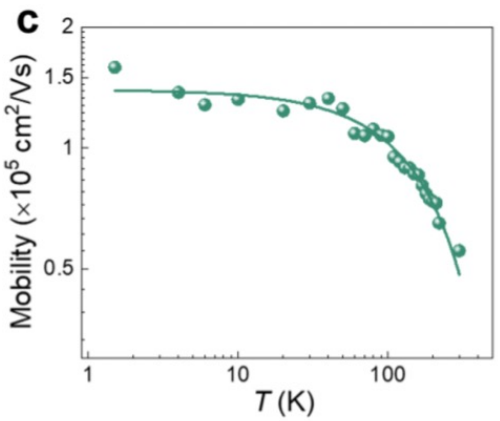


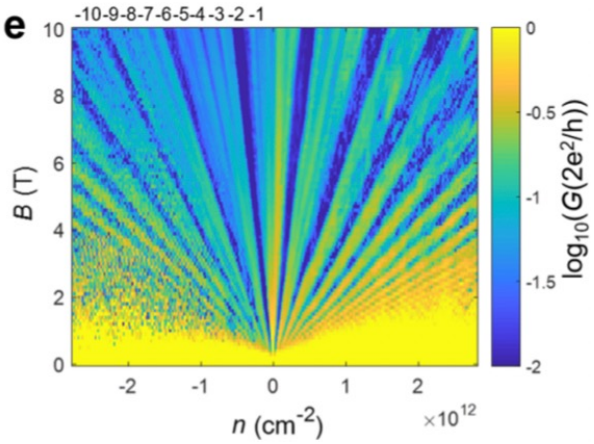
~3.8×10^9 cm^{-2}



Science 367.6480 (2020): 903-906

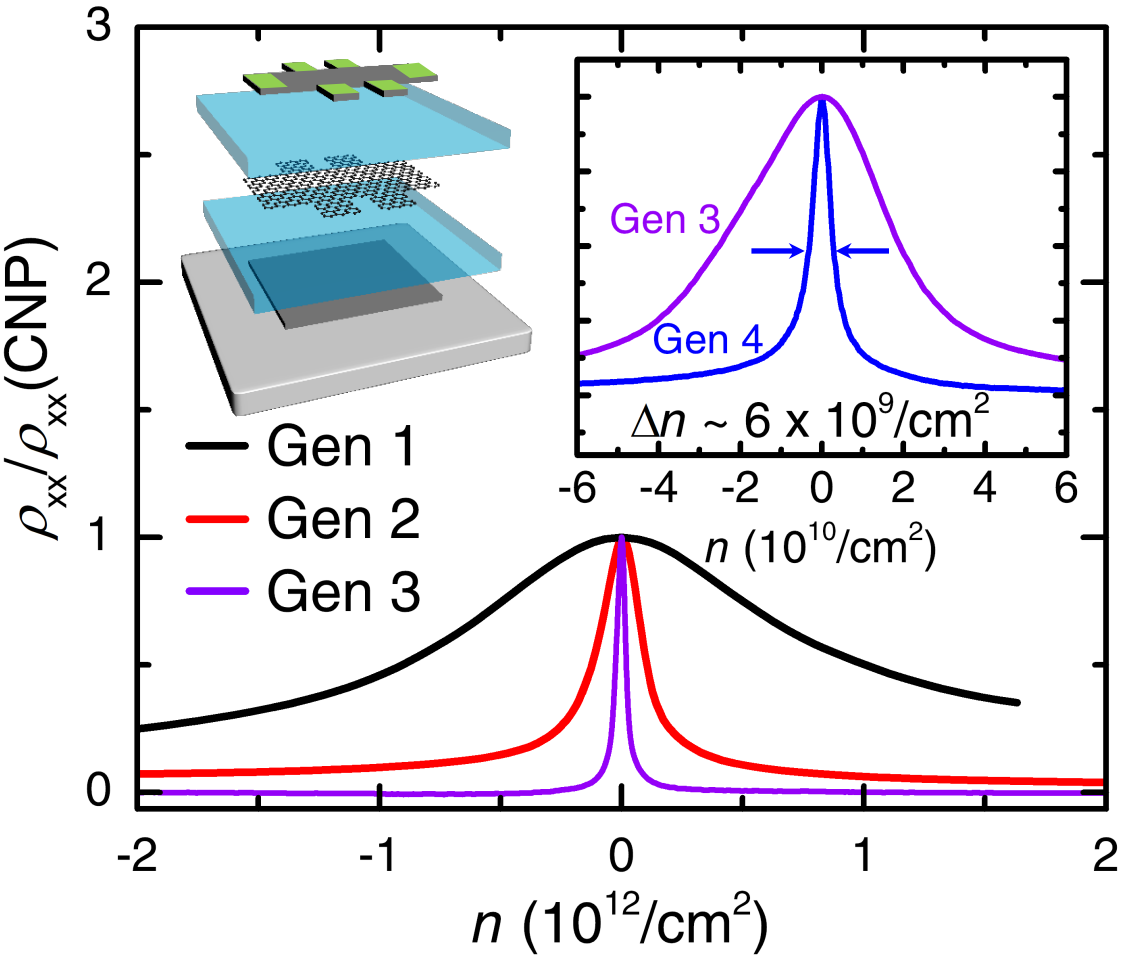






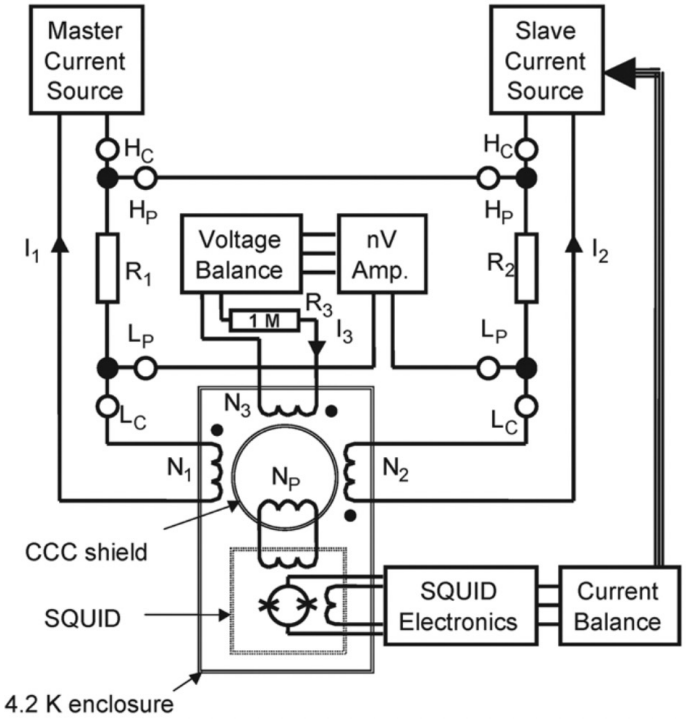
Liu* et al. ACS Nano 2023, 17, 17, 16587–16596

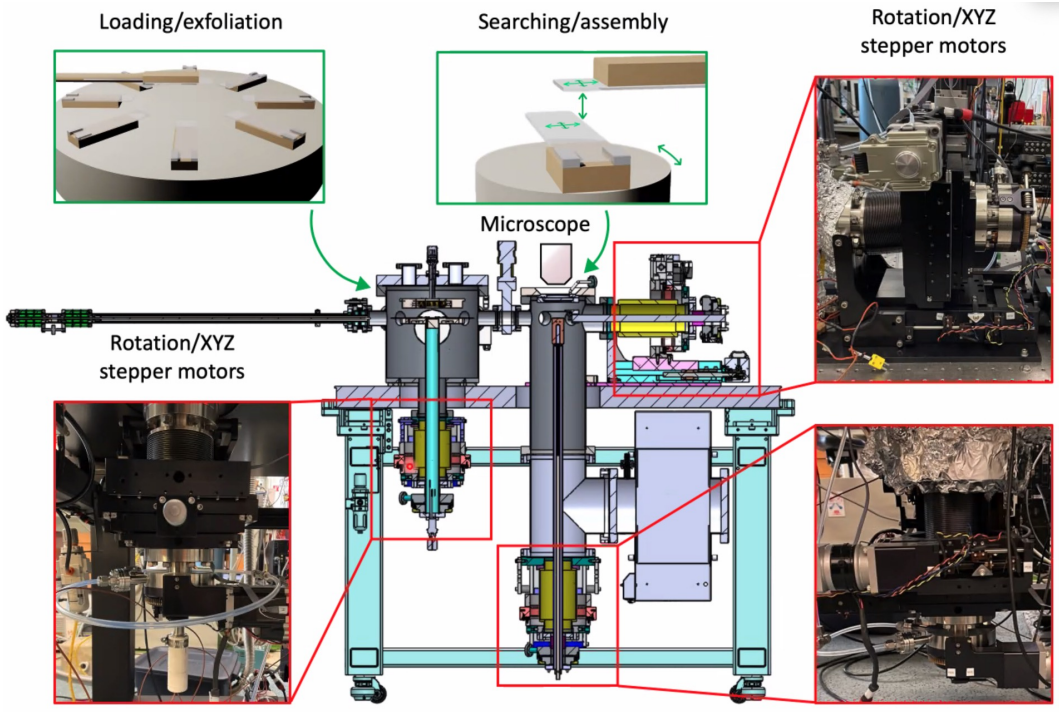
Spatially-Resolved Modulation doping



Spatially-Resolved Modulation Doping based on Ultraclean Quantum Materials!

Existing Obstacles & Solutions





CCC Measurement Setup

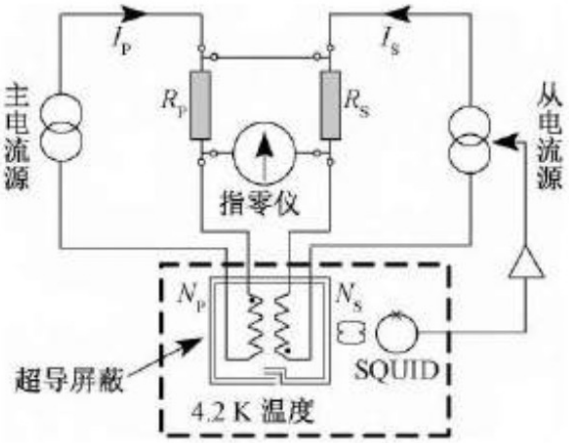
Ultrahigh Vacuum Transfer Setup

Cryogenic Limited Magnicon

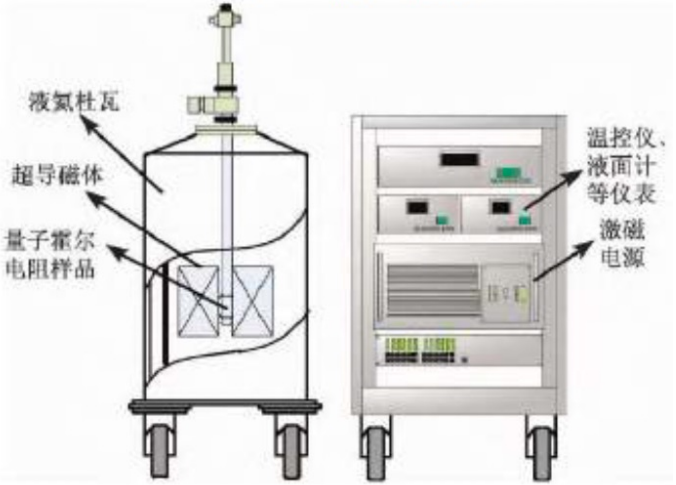
研究涉及的关键技术

关键技术问题3：量子电阻比对及测量不确定度抑制

CCC电桥原理图



QHRS测量系统



- CCC电桥易受外磁场干扰而**失锁**，要求低频**磁屏蔽**环境
- 比对电路易受制冷和磁场激励干扰，要求实现**电磁屏蔽**

Fundamental Science Questions

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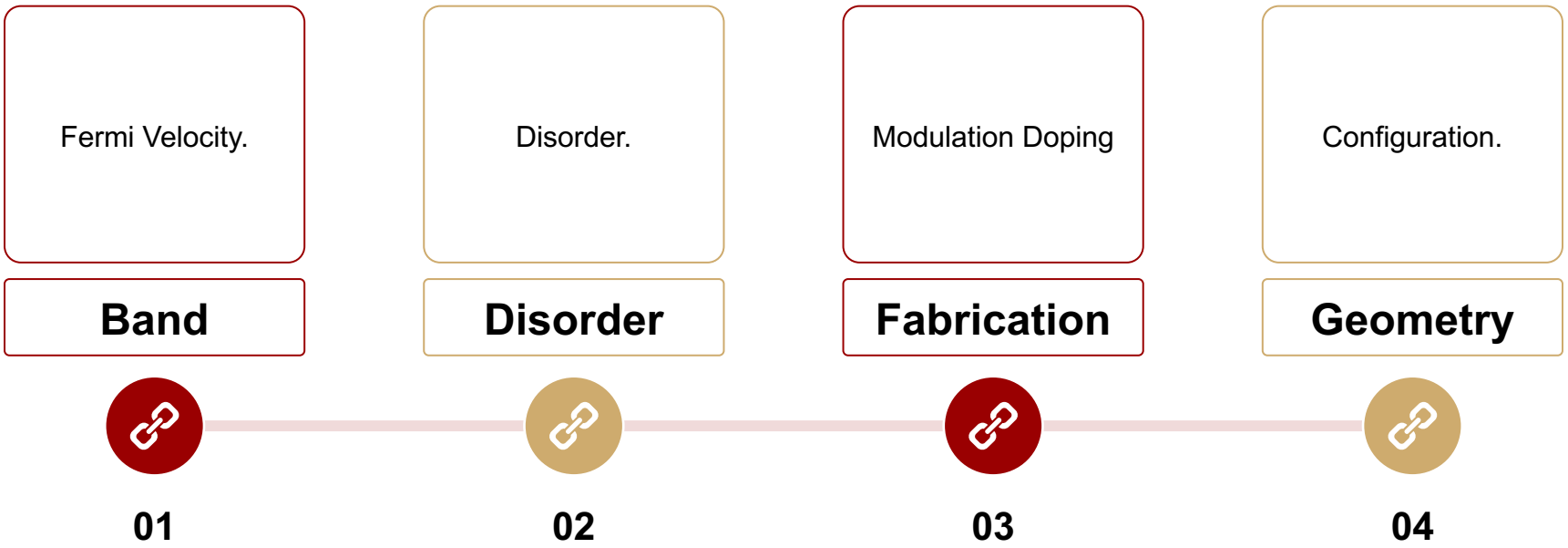
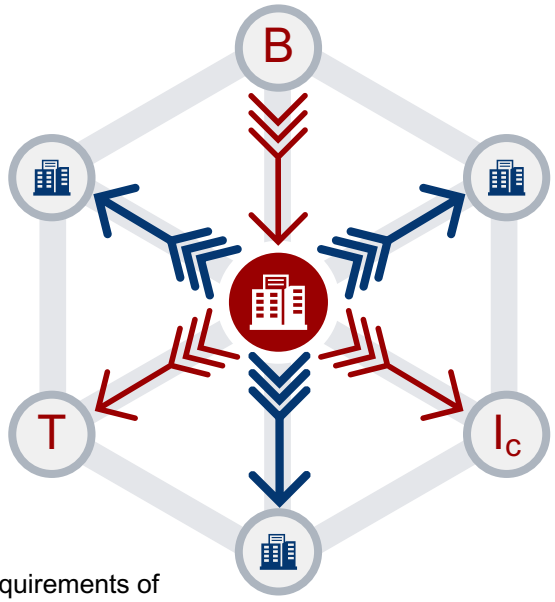


Unified efforts are needed to drive it below the ppb level!

Ultimate Goal

Magnetic Field

- The lower the better.
- ……



Accuracy

- << ppb.
- ……

Reproducibility

- << ppb.
- ……

Temperature

- Higher T could lift the requirements of cryogenics.
- ……

Current

- Higher Current could improve S/N.
- ……

Uncertainty

- << ppb.
- ……

Thanks for your listening!