Quantum Hall effect in graphene: Breakdown and hot electron effects

Luchon May 2015

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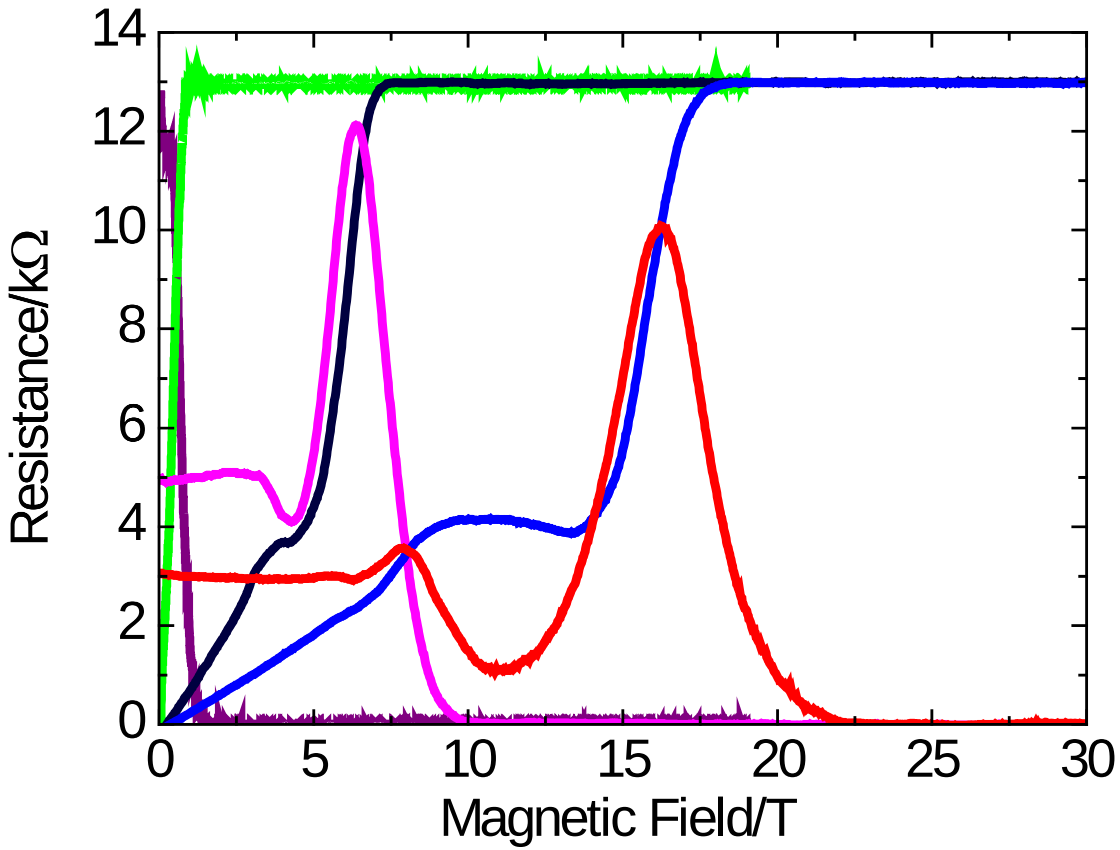
Outline

- Energy loss rates in graphene
- Quantum Hall effect in graphene
- Magnetic field and temperature dependence
- Hot electrons and Bootstrap electron heating model

QHE in epitaxial graphene



- Exceptionally wide quantised ν=2 plateau at T=2K
- Well defined zero resistance state for a wide range of carrier densities

Alexander-Webber *et al*., PRL **111**, 096601 (2013)

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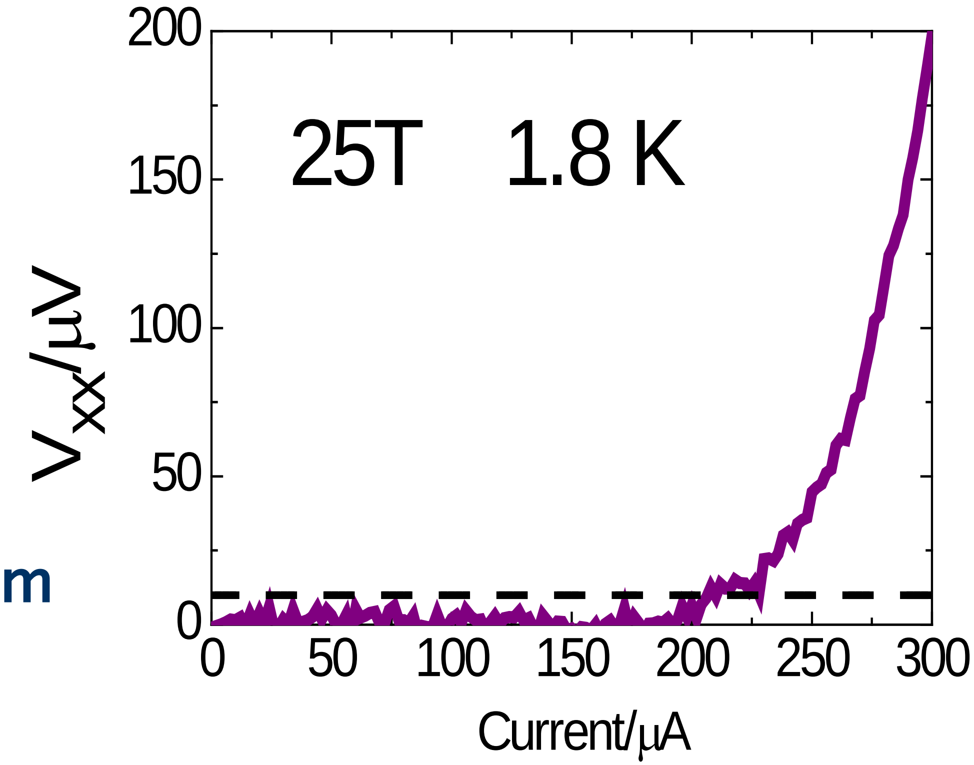
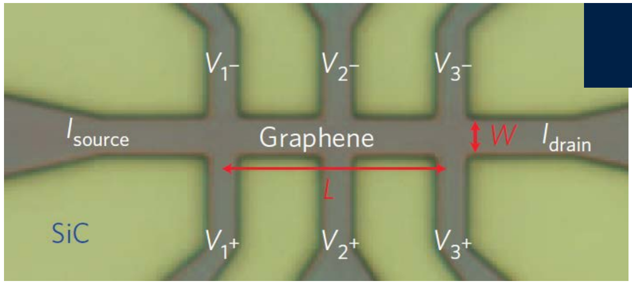
High current breakdown of QHE

- QHE breakdown = sudden onset of longitudinal resistance
- Breakdown defined at Vxx=10μV
- Remarkably high breakdown currents: over 200μA in a **5μm wide** Hall bar at T=1.8 K
- **43A/m** at 25T, over an order of magnitude higher than GaAs

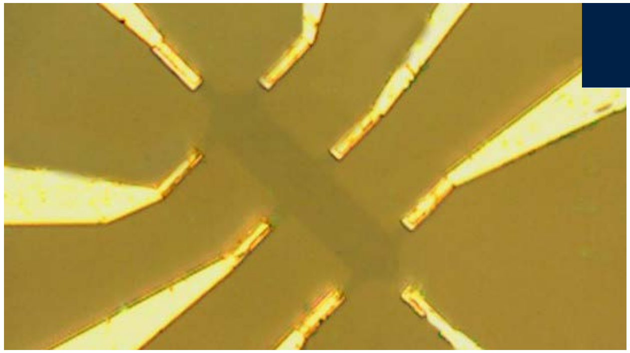


Magneto-transport in 3 different graphenes



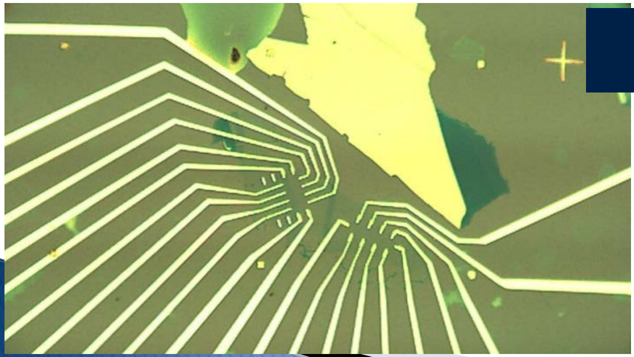
Epitaxial

$1 – 16 \times 10^{11}$



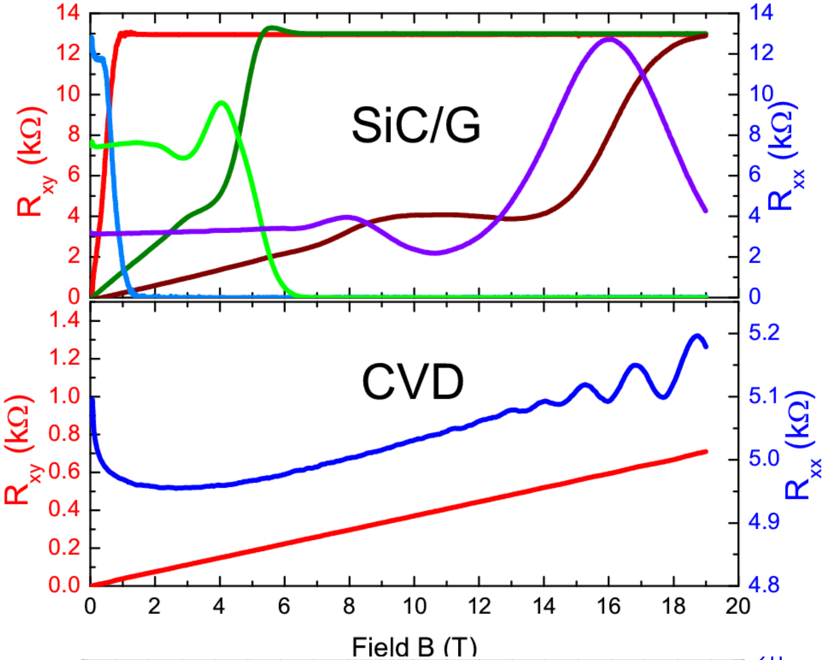
CVD

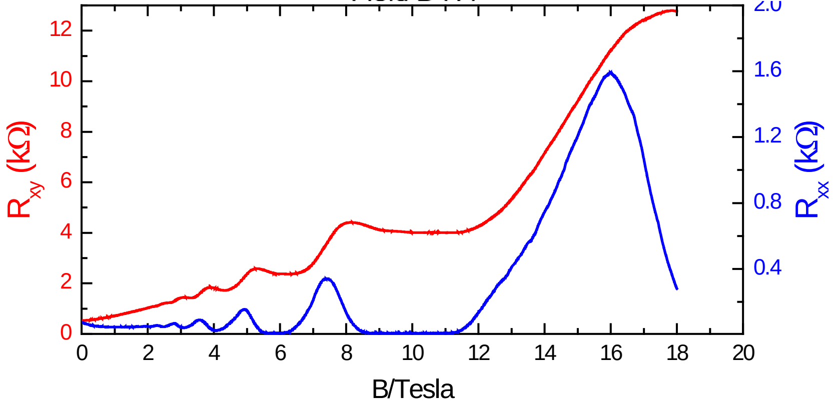
$0.8–1.6 \times 10^{13}$



Exfoliated

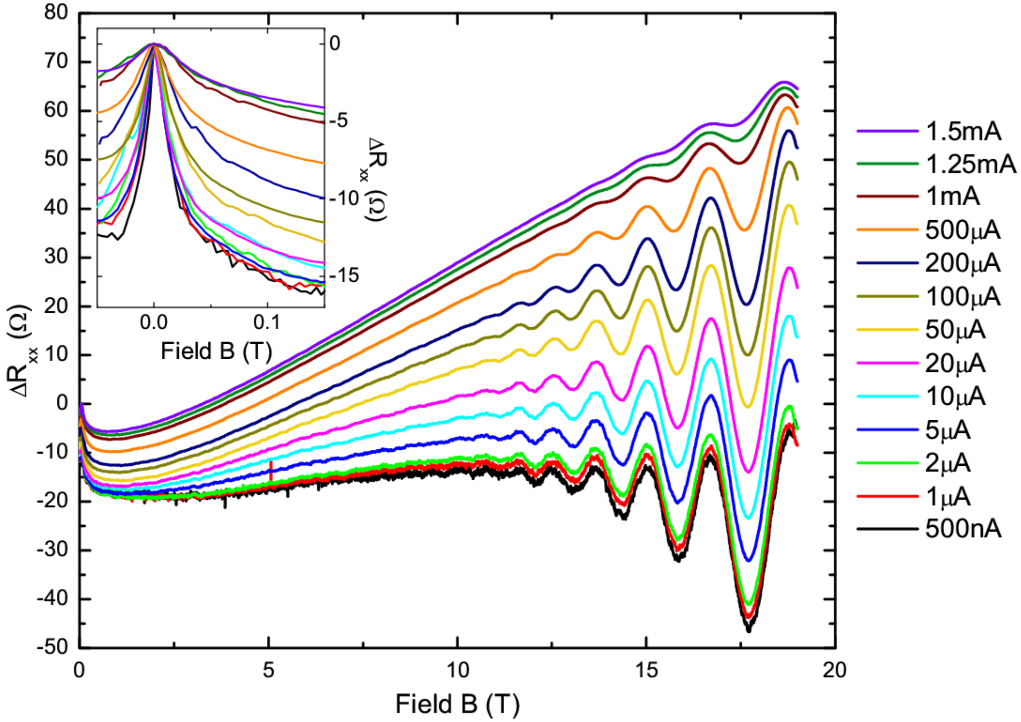
1.5×10^{12}





Heat Carriers with Electric Field

CVD graphene



Theory, (Ando, Lifshitz & Kosevich)

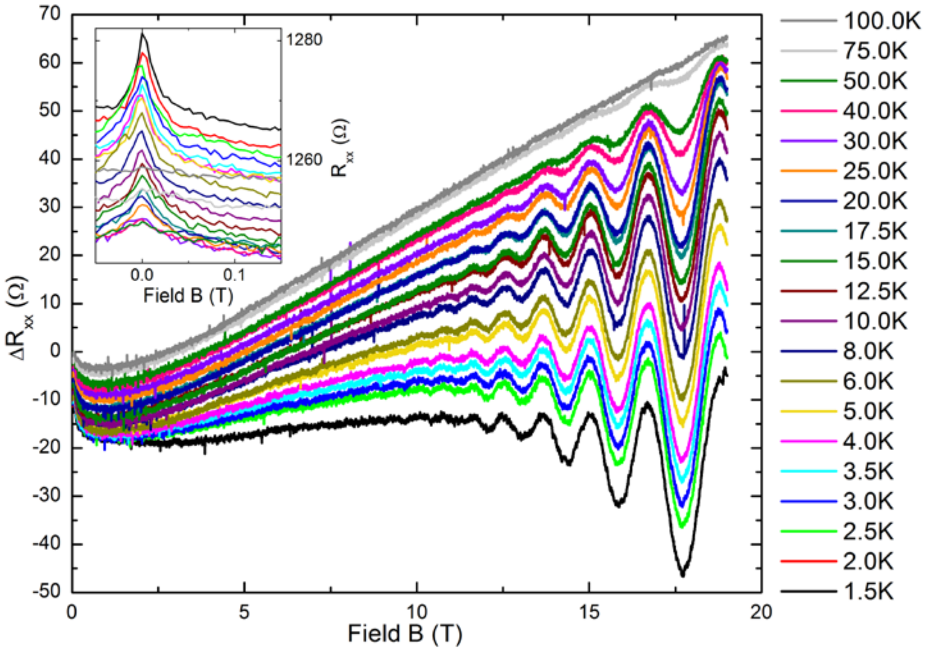
$$\frac{\Delta\rho}{\rho} = f(\omega_c)\frac{\chi}{\sinh\chi}$$

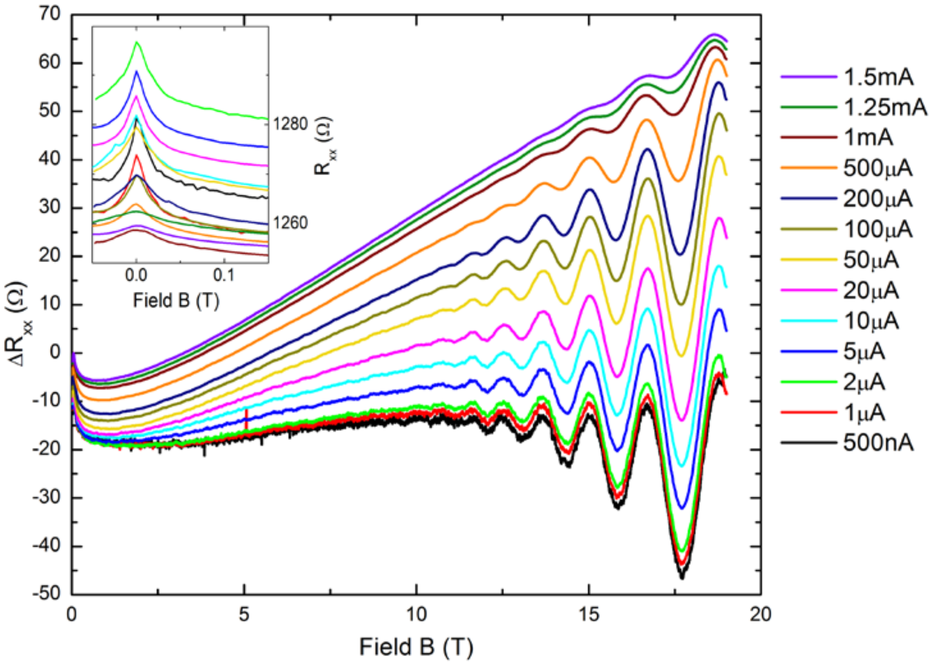
$$\chi = 2\pi^2\frac{kT}{\hbar\omega_c}$$

Deduce carrier temperature as a function of input power

$$= \quad I^2\rho_{xx} = \nu\sigma_0 E^2$$

Measure electron Temperature



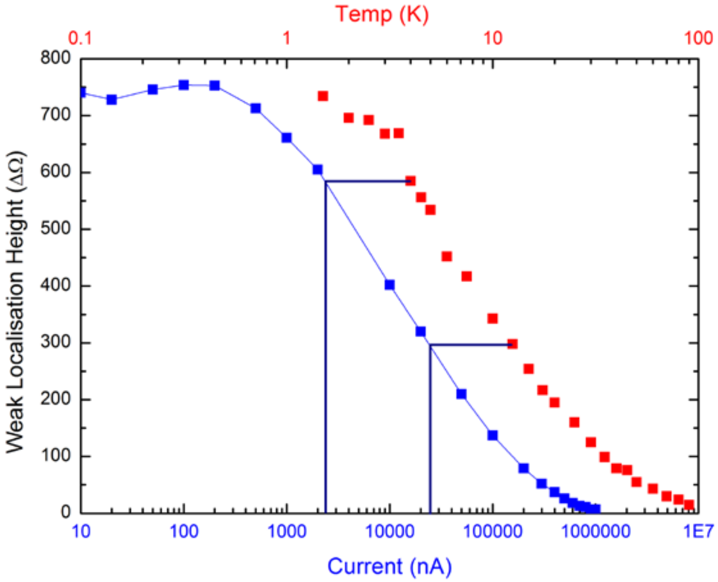


Temperature dependence matched to: Current dependence

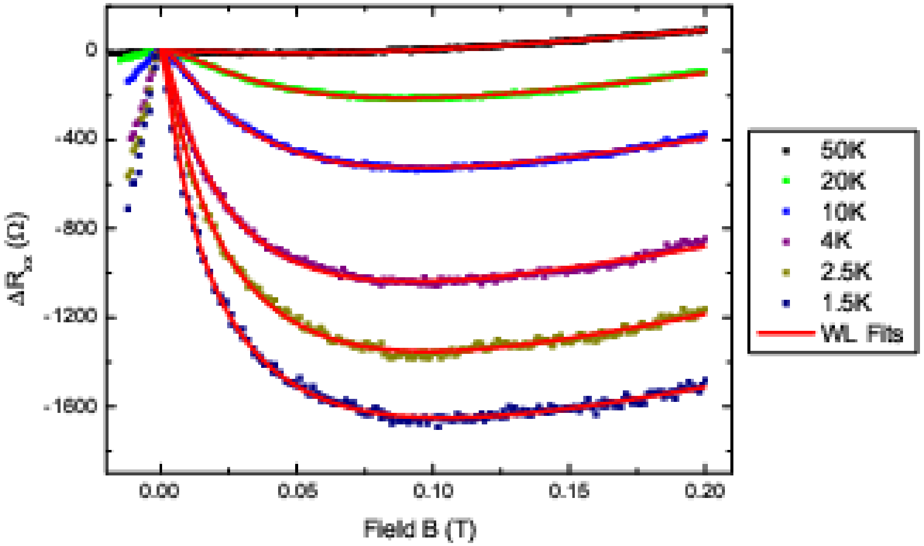
Total input power = n_e x energy loss rate per carrier (**P** (**T_e**))

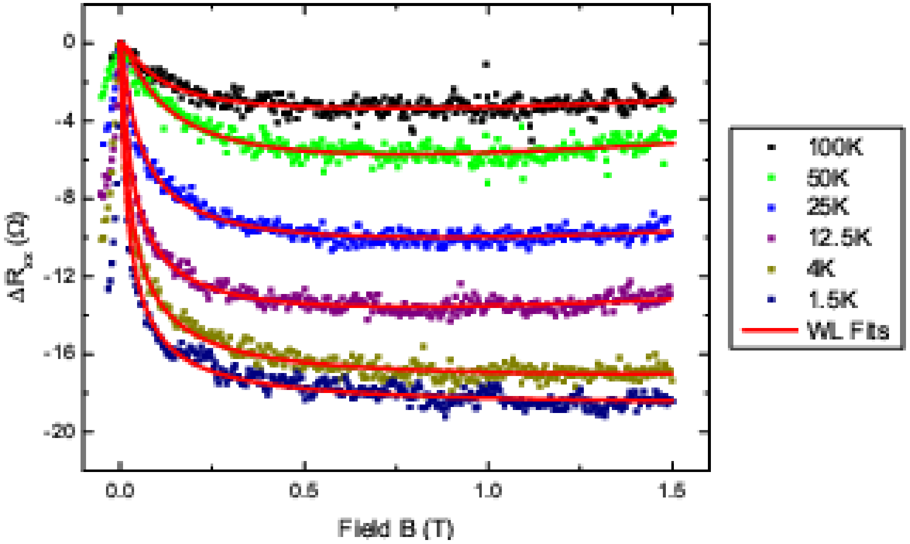
$$n_e P\,(T_e) = I^2\,\rho_{xx} = \nu\sigma_0 E^2$$

Weak localisation peak



WL peak depends on electron temperature due to electron–electron scattering



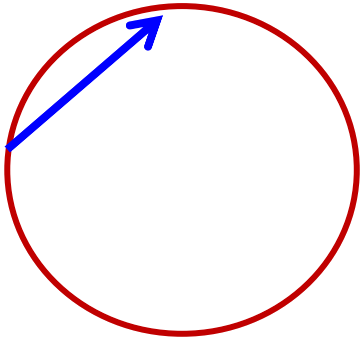


Energy Loss rate per carrier

Bloch–Gruneissen

(low temperature) limit:

$k_B T_{BG} = 2 v_s k_F \hbar$ (20–250K)



$$P = \alpha(T_e{}^4 - T_L{}^4)$$

$$P = \frac{\pi^2 k_B{}^2 T_e{}^2}{3 E_F \tau_e}$$

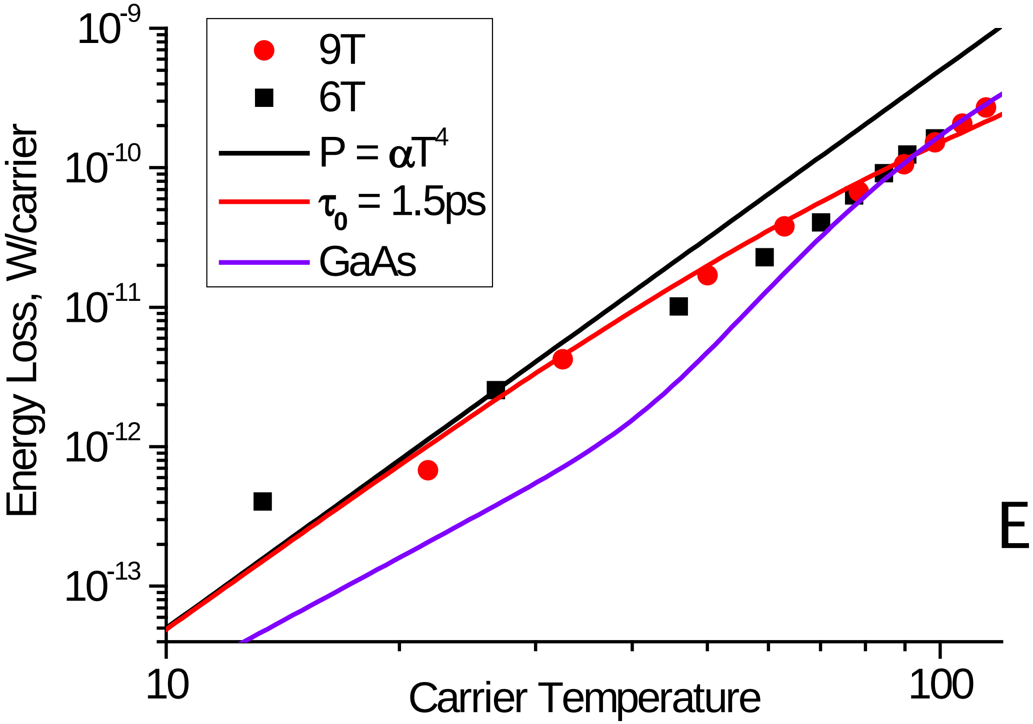
Energy relaxation time, τ_e

Low temp. theory[1] Deformation Pot. Scatt. $\tau_e = \dfrac{\pi^2 k_B{}^2 T_e{}^2}{3 E_F \alpha T_e{}^4} + \tau_0$

Limit τ_e to 1.5 ps due to phonon relaxation (τ_0)

1: Kubbakadi, Phys. Rev. B79, 075417 (2009)

Energy Loss rate per carrier



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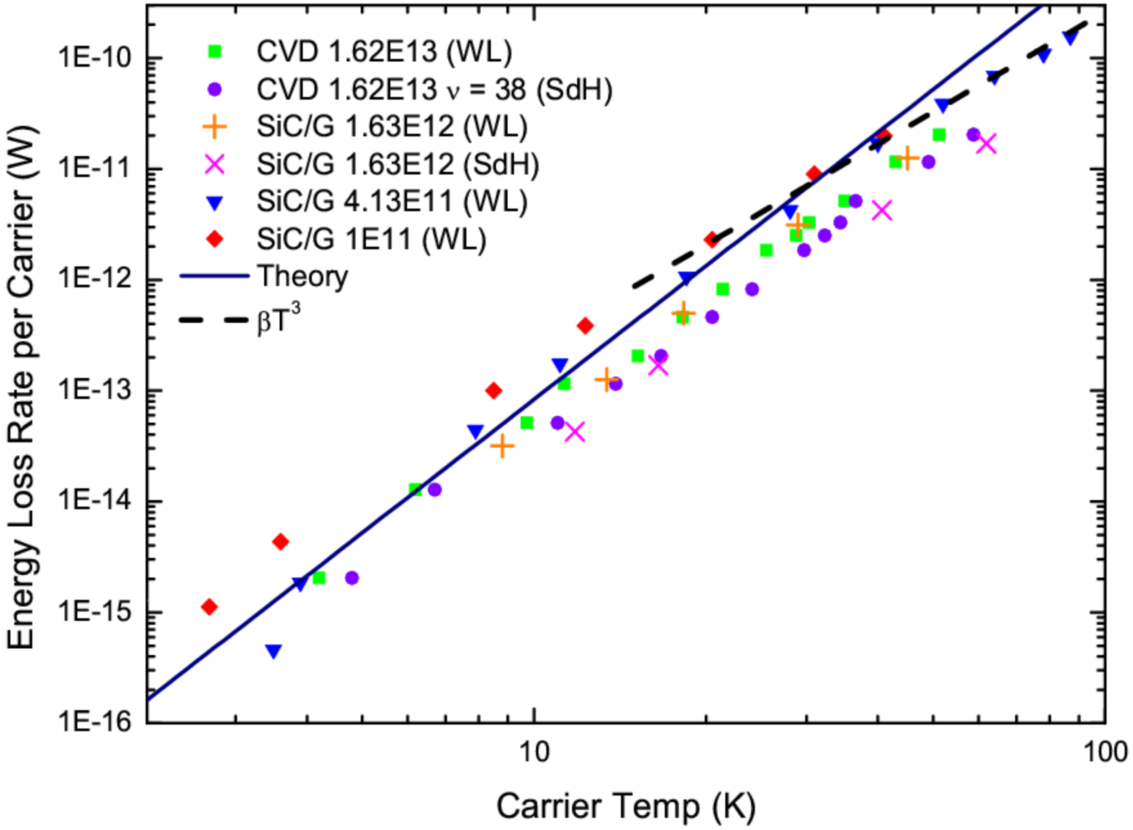
Energy Loss rates for all densities

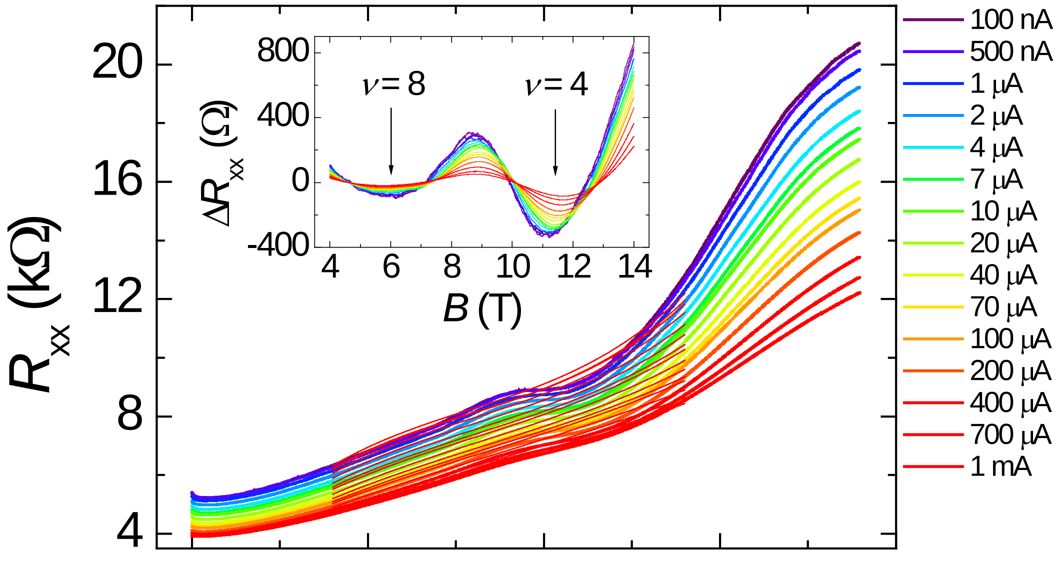


Low temperature T⁴ dependence is generic

Some weakening at higher temperatures

Define loss rate coefficient from: $P = \alpha({T_e}^4 - {T_L}^4)$

Bilayer graphene

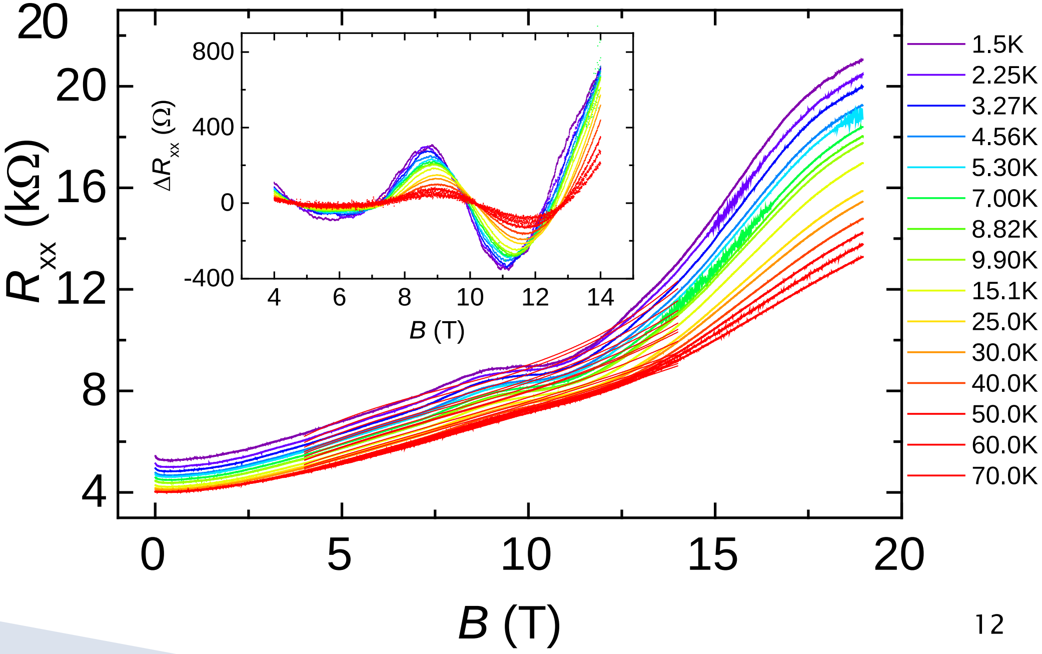


Current dependence (from 100nA to 1mA) at a fixed low ambient temperature (1.4K)

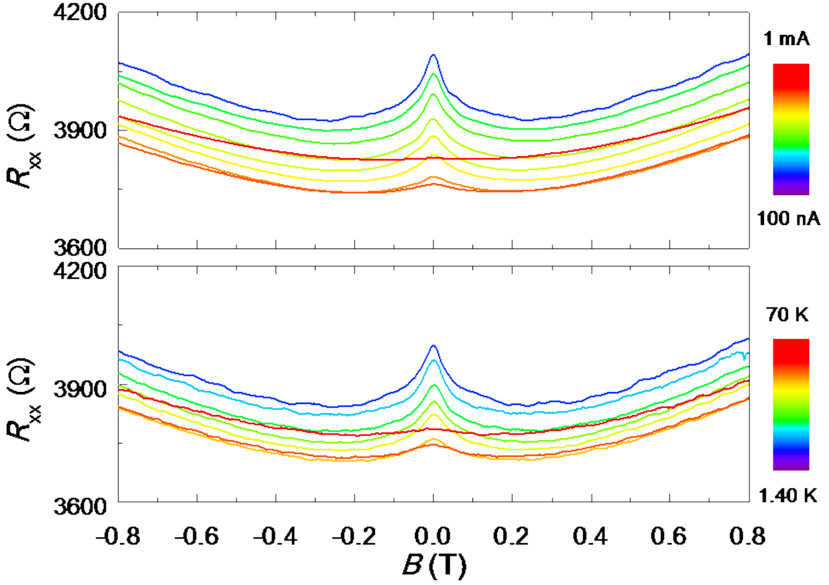
Background subtraction using 3rd order polynomials

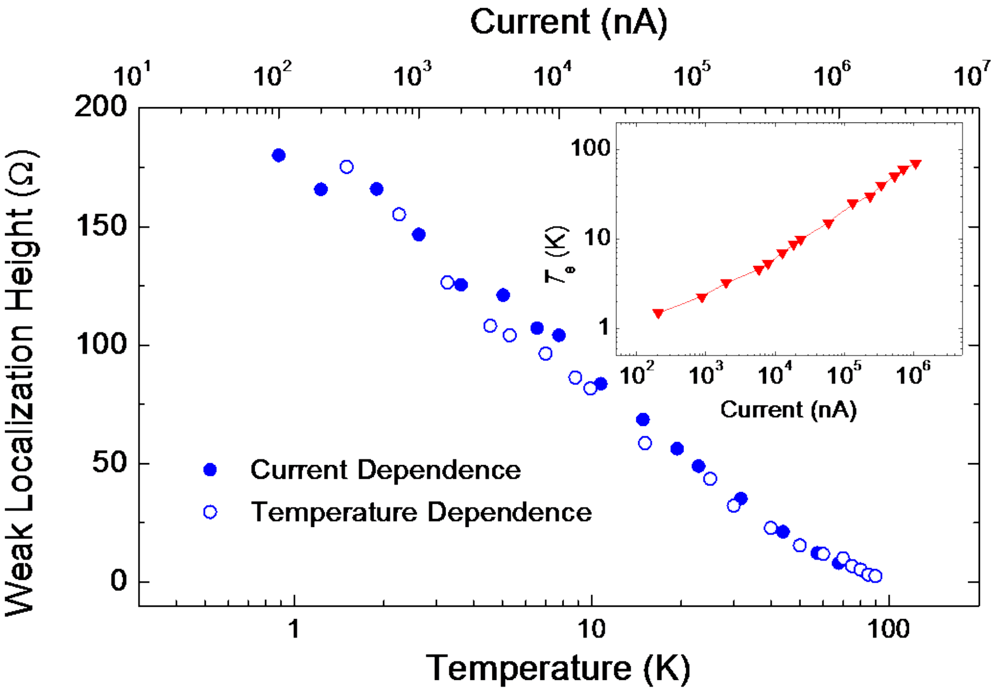
Filling factors 4 and 8 are observed

Temperature dependence (from 1.5K to 70K) at a fixed low current (100nA)

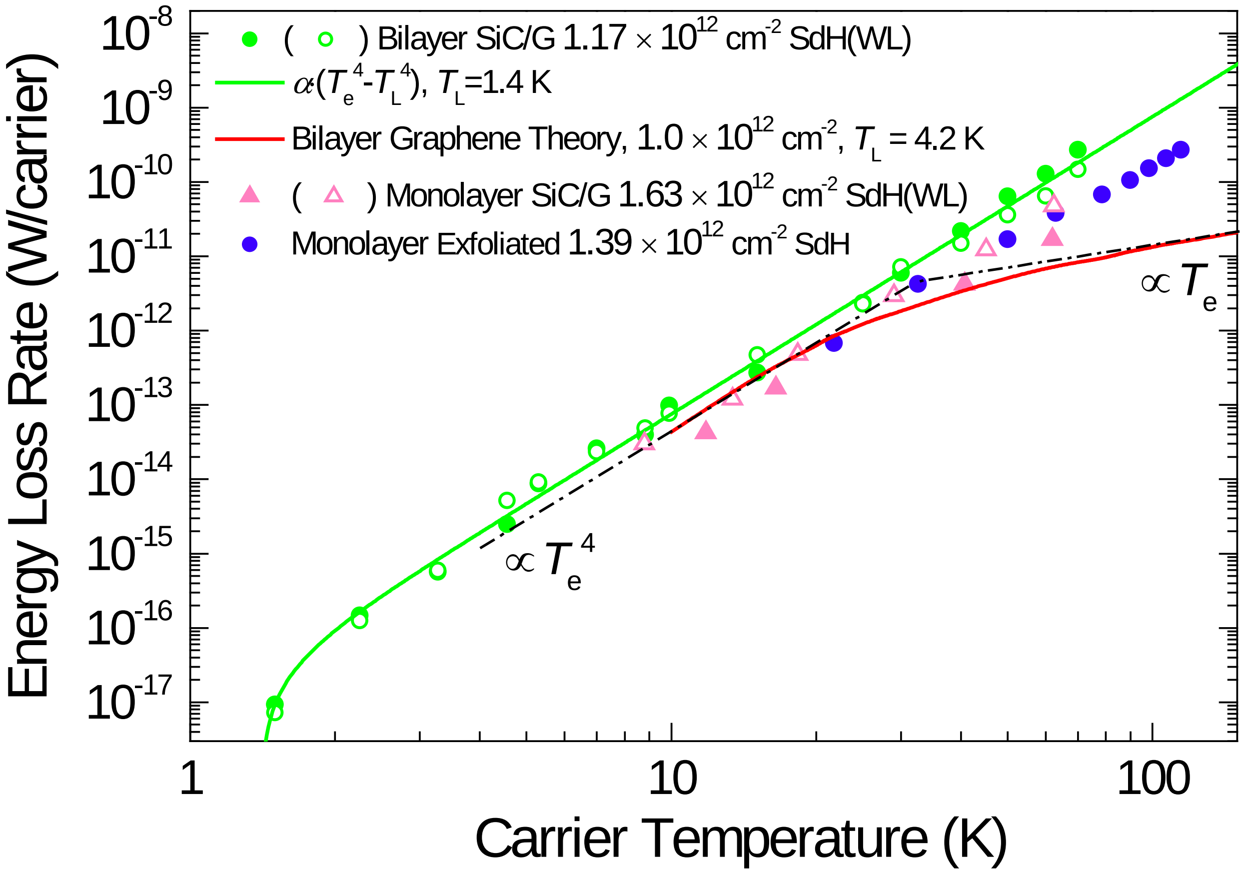


Bilayer Weak localisation





Energy Loss rates for all graphenes

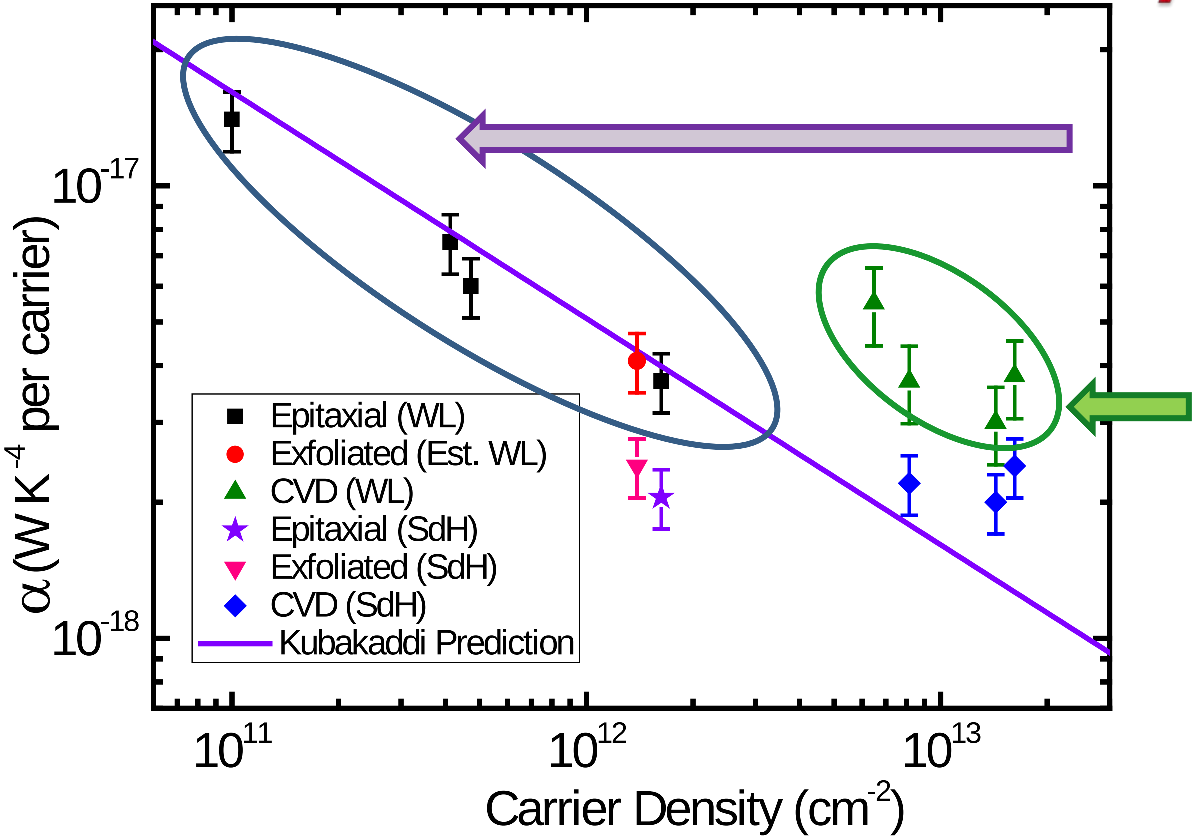


Low temperature T^4 dependence is generic

Some weakening at higher temperatures

Define loss rate coefficient from: $P = \alpha(T_e{}^4 - T_L{}^4)$

Density dependence of Energy loss rates – Monolayer graphene



Weak carrier density dependence ~ $n^{-0.5}$

Enhanced energy loss in CVD (more disordered) graphene

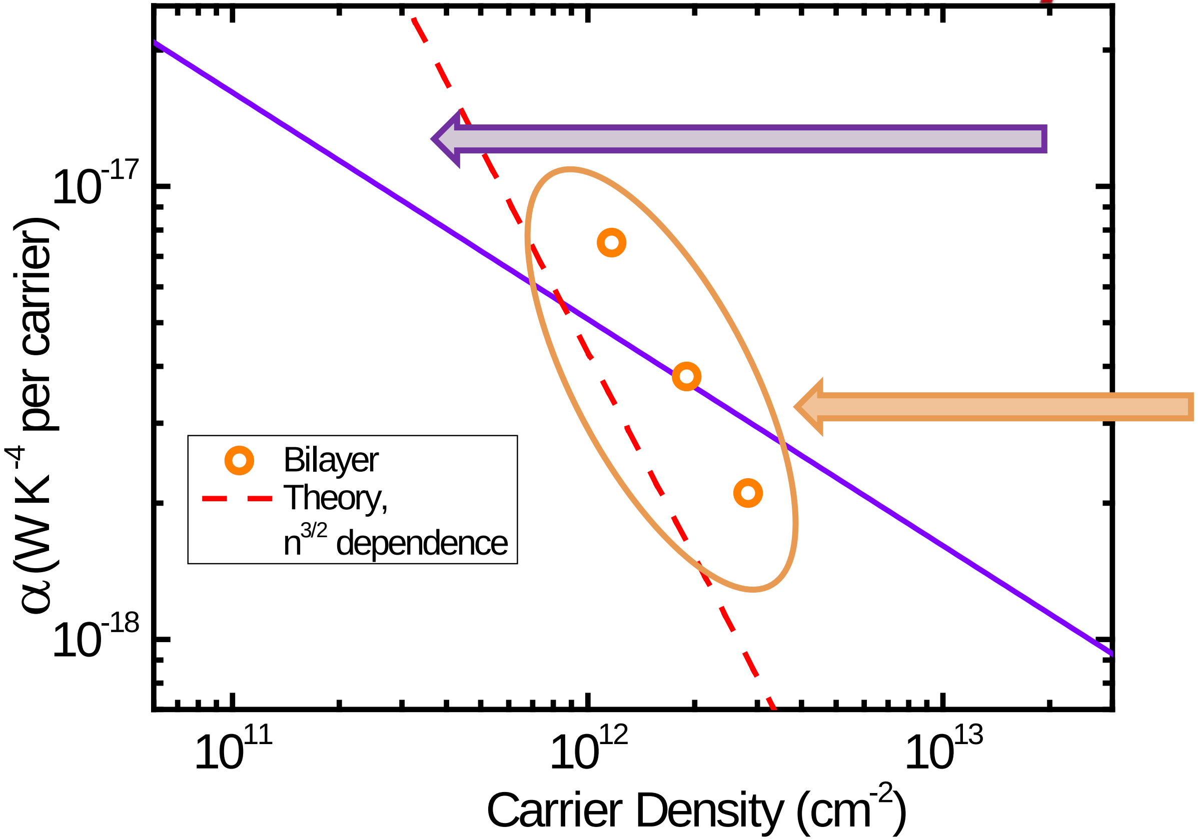
? Enhanced energy loss due to ‘Supercollisions’?

Theory : Song et al. PRL **109** 10662 (2012)

Experiment: Betz et al. Nature physics **9** 2494

Much weaker than conventional semiconductors ~ $n^{-1.5}$

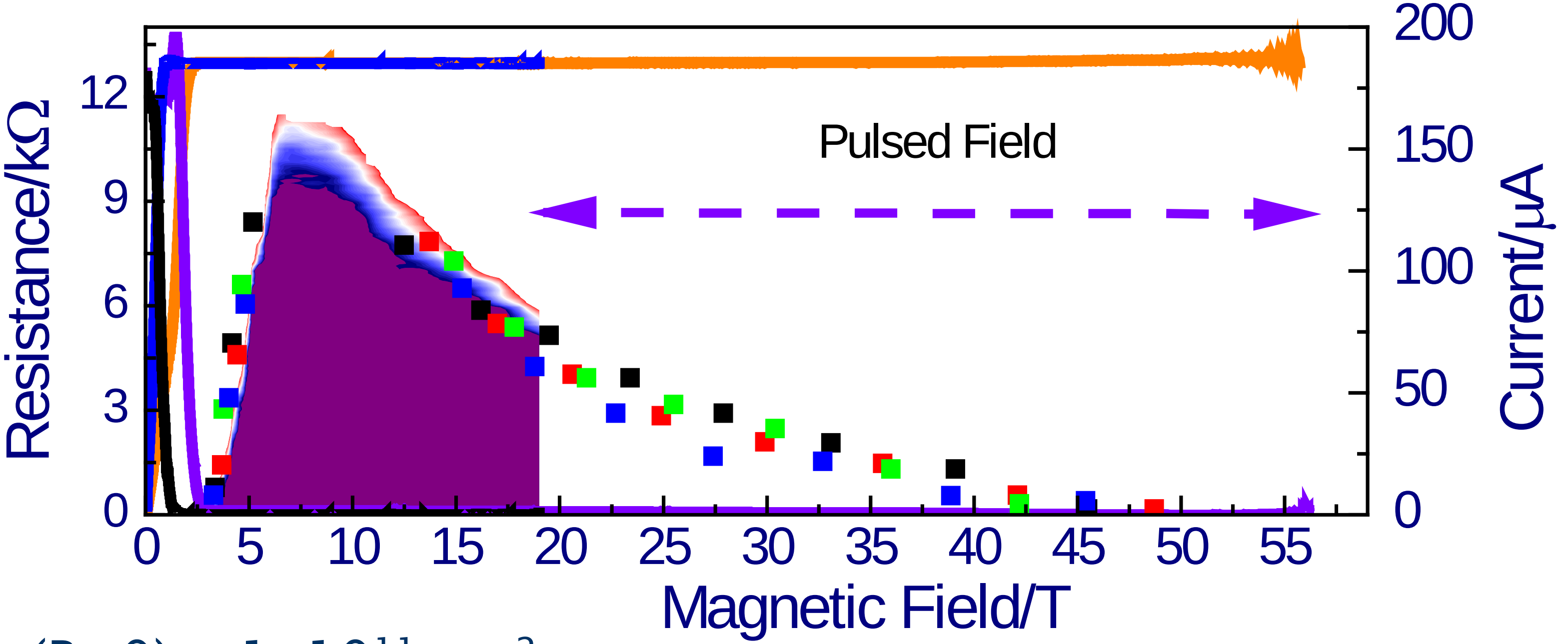
Density dependence of Energy loss rates – Bilayer graphene



Monolayer density dependence ~ $n^{-0.5}$

Bilayer behaves like conventional semiconductors with loss rate ~ $n^{-1.5}$

QHE at low carrier densities



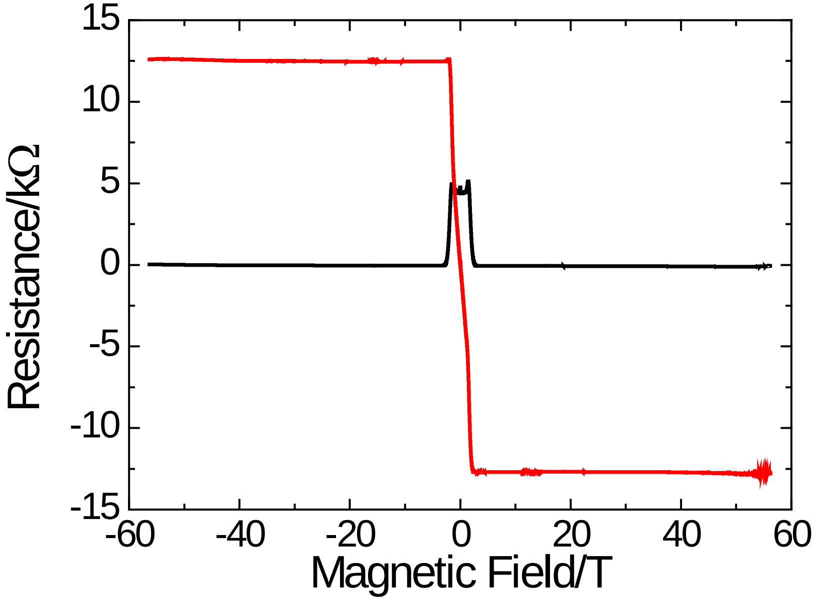
$n(B=0) \sim 1 \times 10^{11} cm^{-2}$

At 7T $I_C = 140 \mu A$, $j_c = 4 A/m$

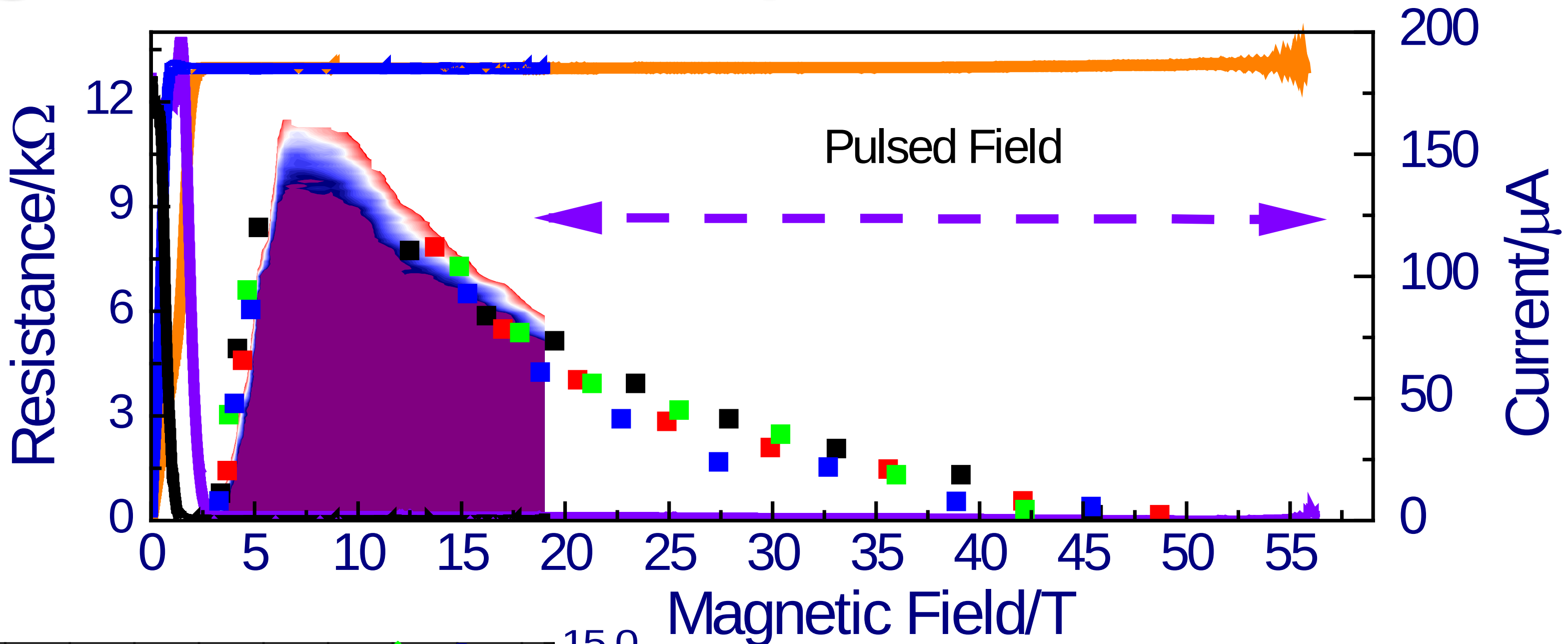
Carrier density increasing

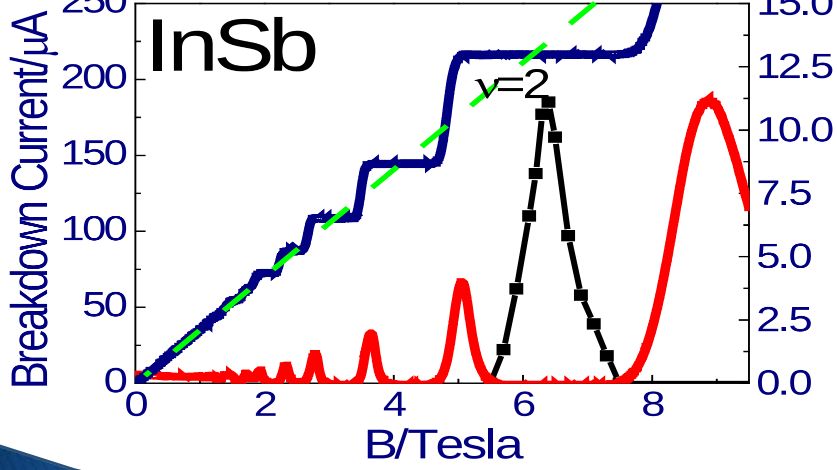
$\nu(50T) > 1.6$

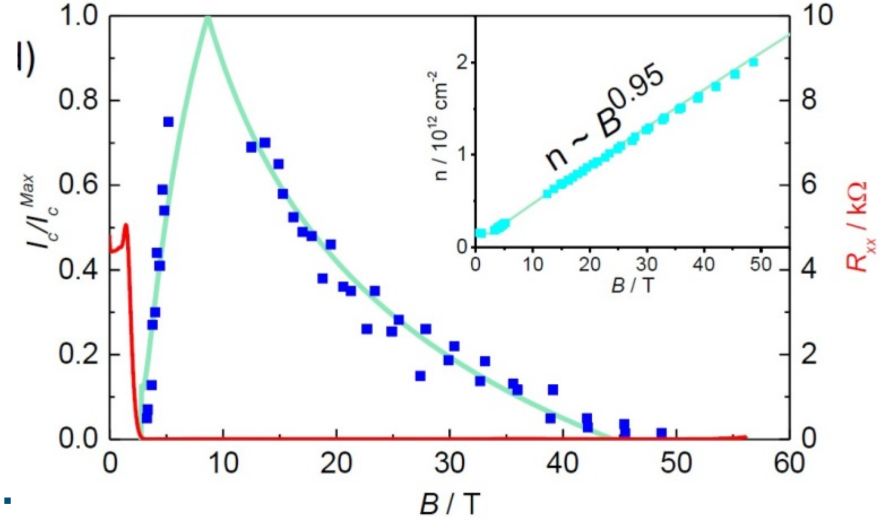
$n(50T) \sim 2 \times 10^{12} cm^{-2}$



Magnetic Field Dependence

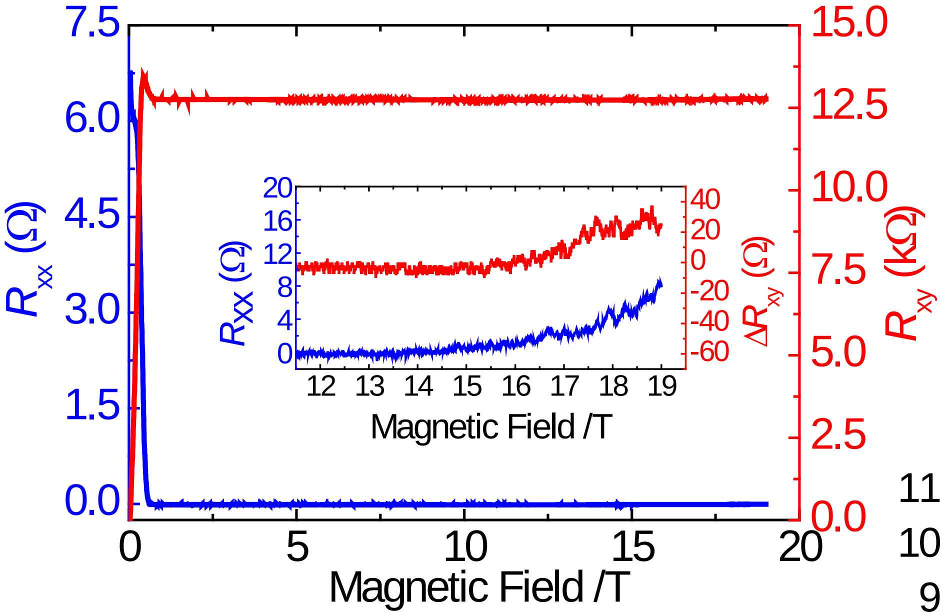






Alexander-Webber et al.
PRB 86, 045404(2012)

QHE at Ultra-low Carrier Density



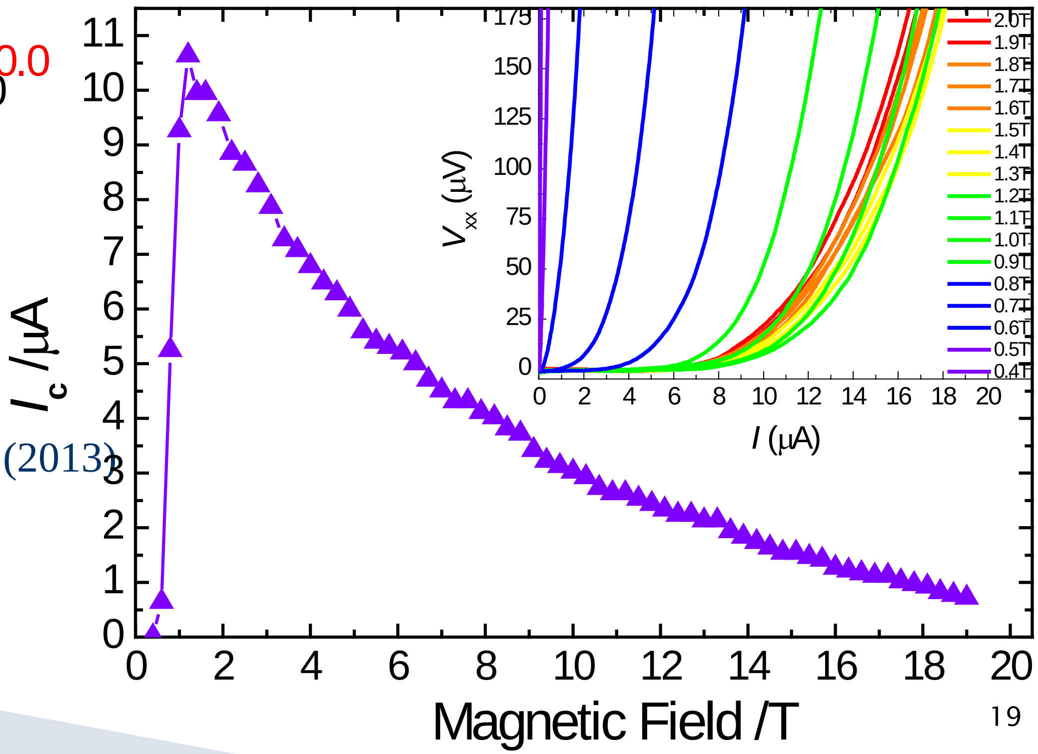
n~1.5x10^{10} cm^{-2} from low field Hall coefficient.

Wide υ=2 quantum Hall plateau and well-defined zero resistance state at 1.4K from 0.6T to ~16T.

Quantum Hall breakdown: maximum breakdown current ~10 μA at 1.2T

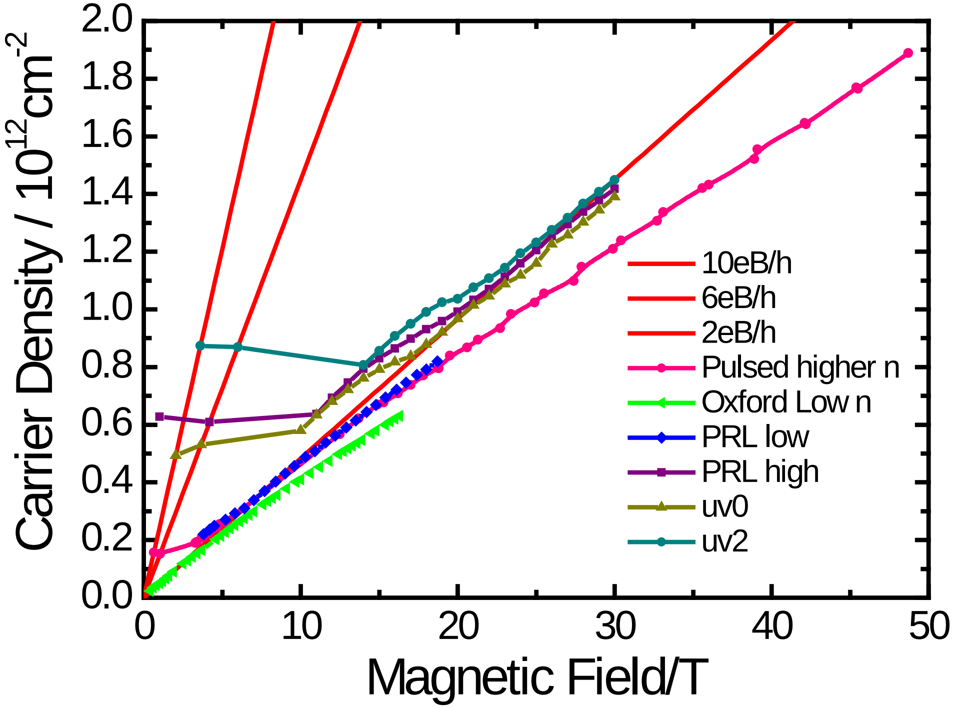
Magnetic field dependent charge transfer from SiC substrate

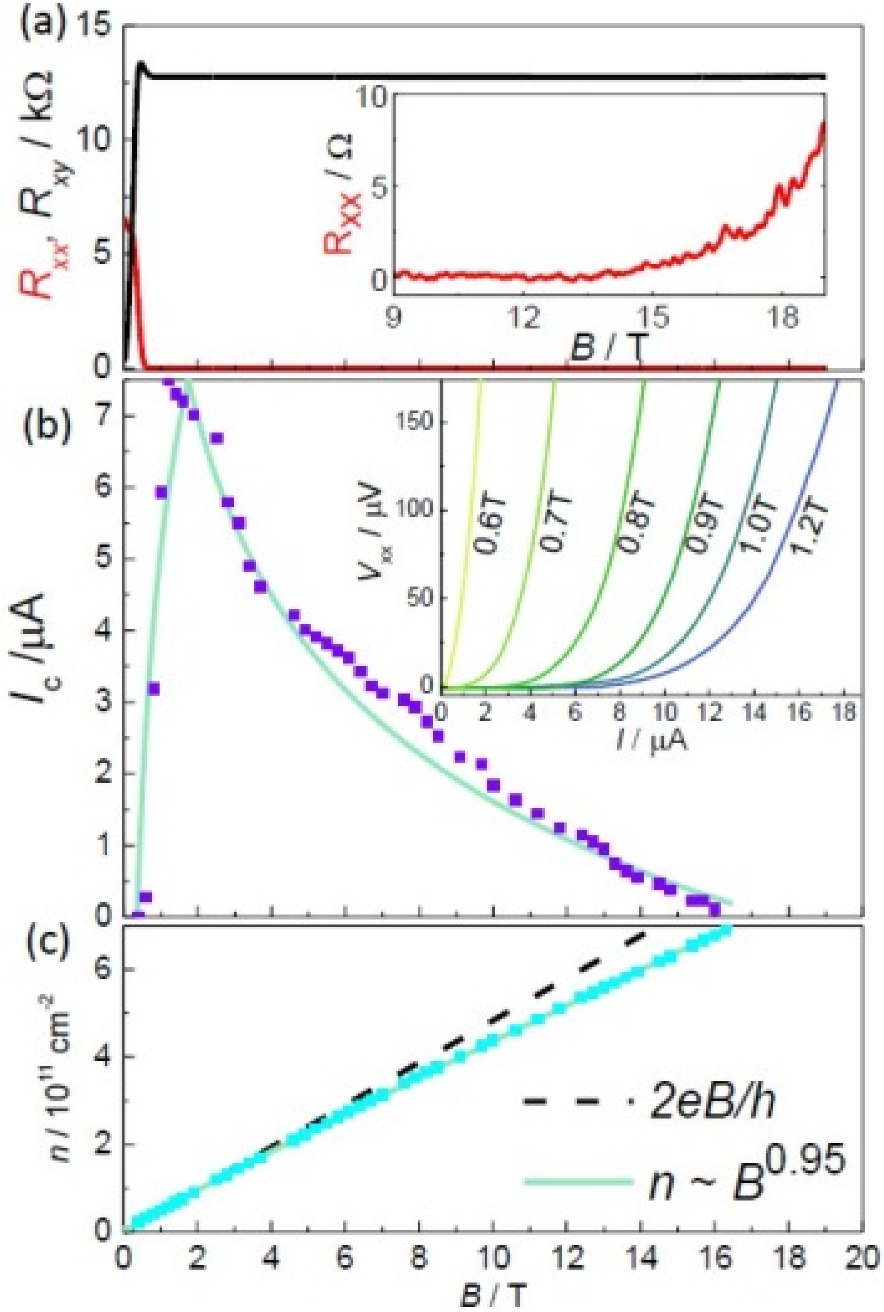
Alexander-Webber *et al.*, PRL **111**, 096601 (2013)
Janssen *et al.*, PRB **83**, 233402 (2011)



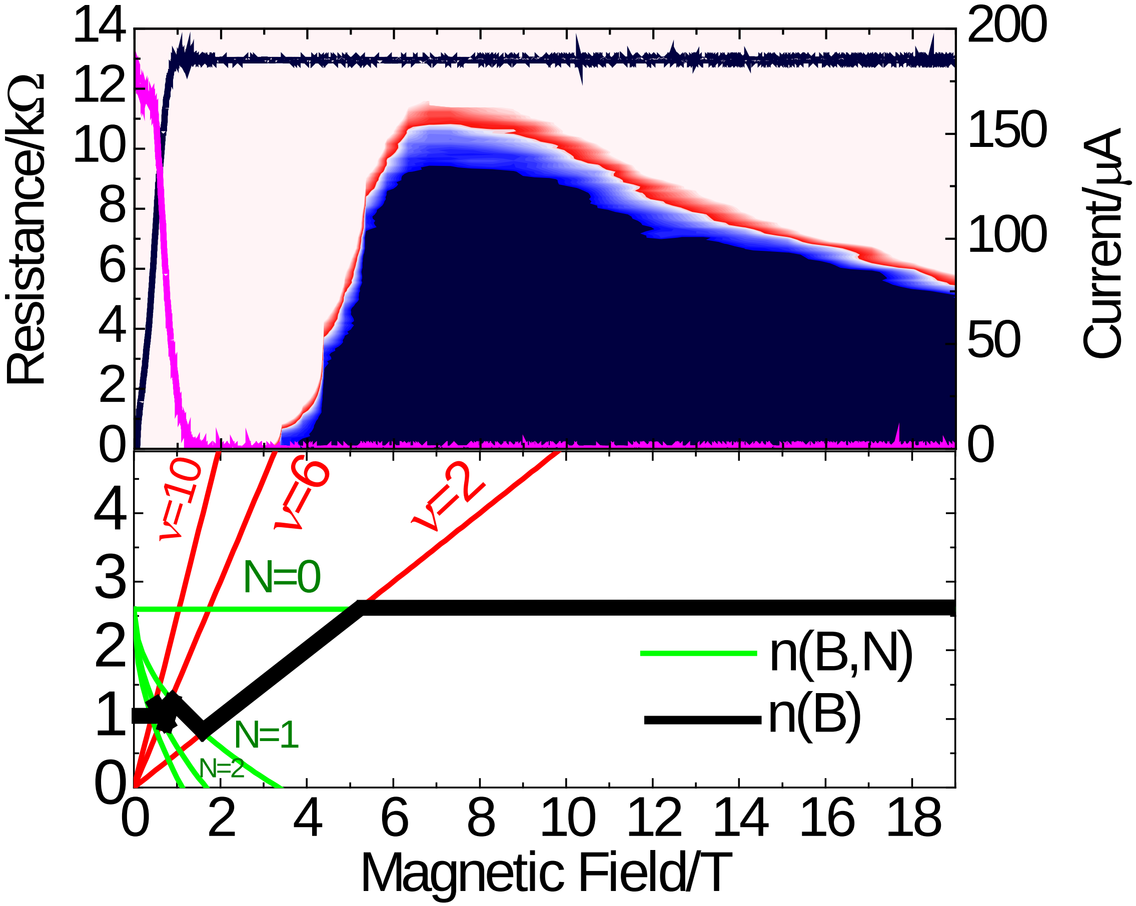
Field dependent carrier density

$n \sim B^{0.95}$





Charge Transfer Model

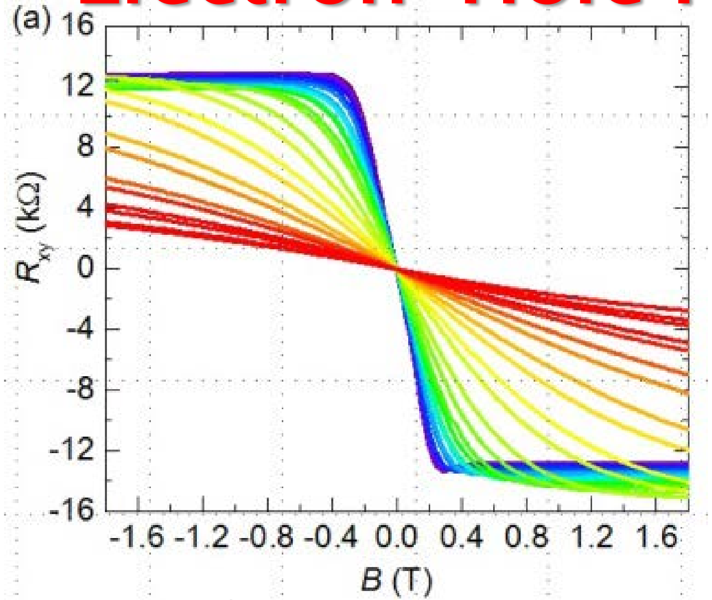


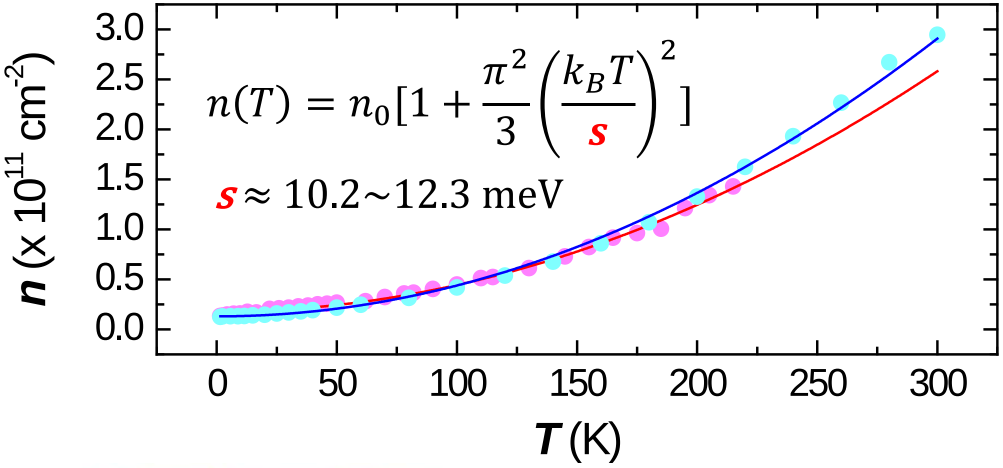
- n~1x10^{11} cm^{-2} from low field Hall coefficient.
- Peak breakdown at 6-8T, suggesting n~3x10^{11} cm^{-2}.
- Peak breakdown field in agreement with charge-transfer model [1,2]
- Model based on unbroadened Landau levels and constant DoS in substrate

[1] Janssen et al., PRB 83, 233402 (2011)

[2] Kopylov et al., APL 97, 112109 (2010)

Intrinsic Excitation in the Presence of Electron-Hole Puddles





$$n(T) = n_0[1 + \frac{\pi^2}{3}\left(\frac{k_B T}{s}\right)^2]$$

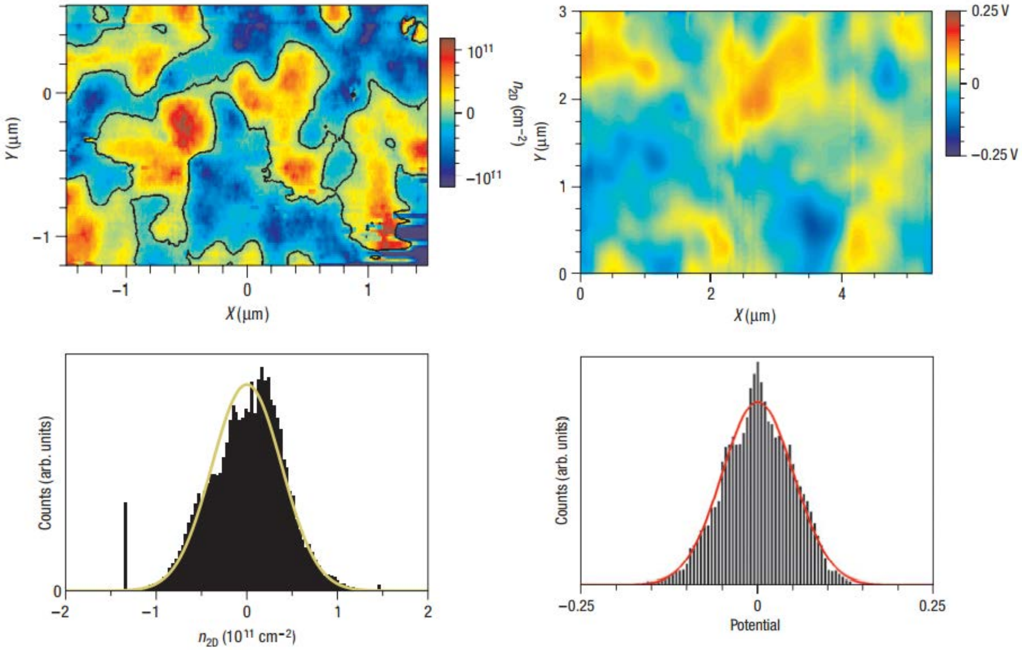
$s \approx 10.2\sim12.3$ meV

Density from two-carrier Hall effect: quadratic increase vs temperature

Electron-hole puddles with Gaussian potential variation:

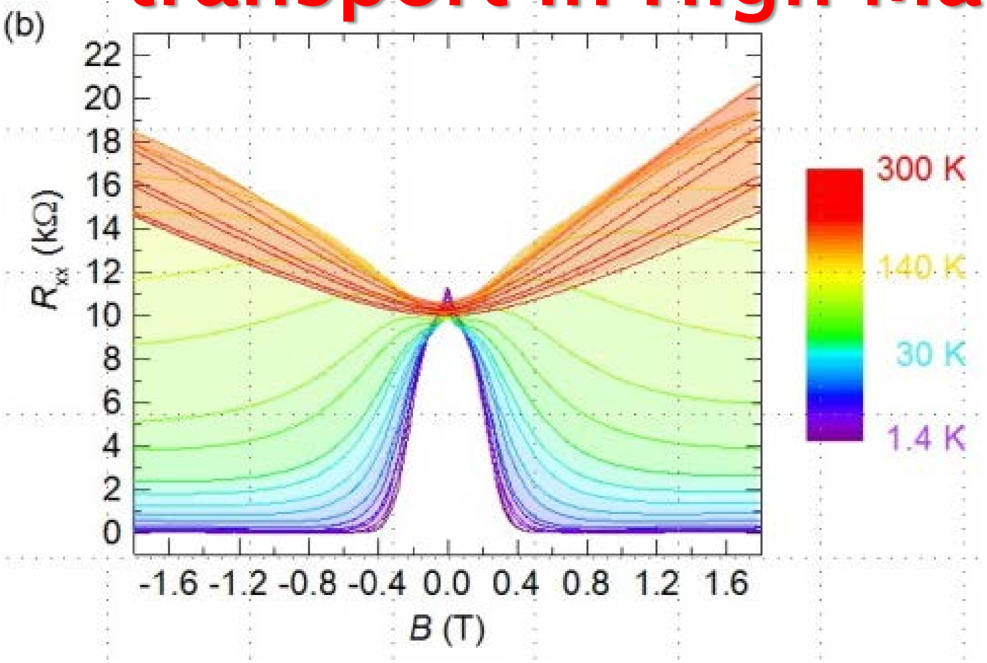
$$P(V) = \frac{1}{\sqrt{2\pi s^2}}\exp(-{V^2}/{2s^2})$$

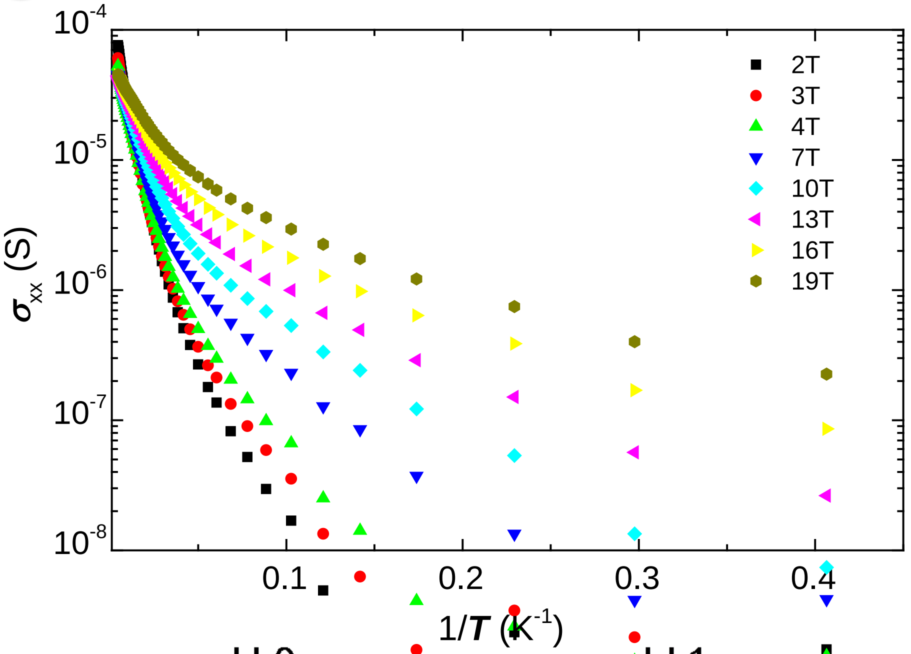
Li, Hwang, and **Das Sarma,** PRB **84**, 115442 (2011)



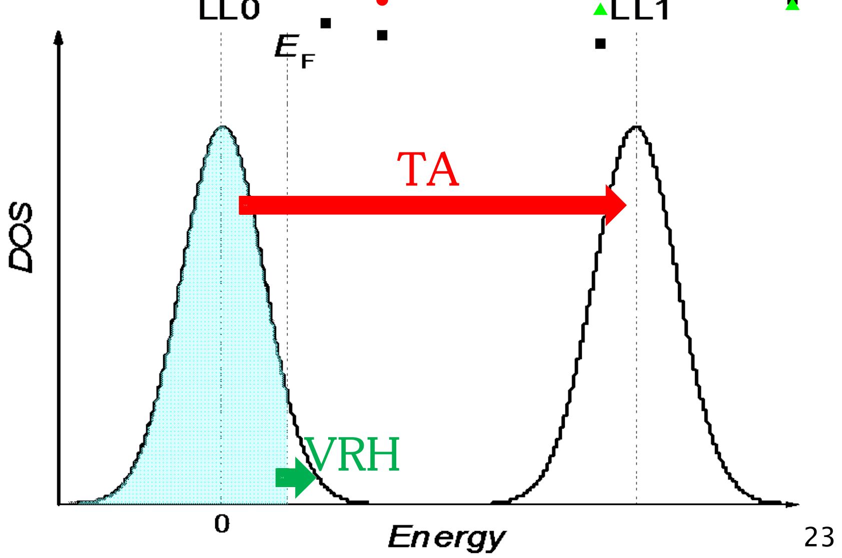
Martin *et al.*, Nature Phys. **4**, 144 (2008)

Temperature-dependent Magneto-transport in High Magnetic Fields

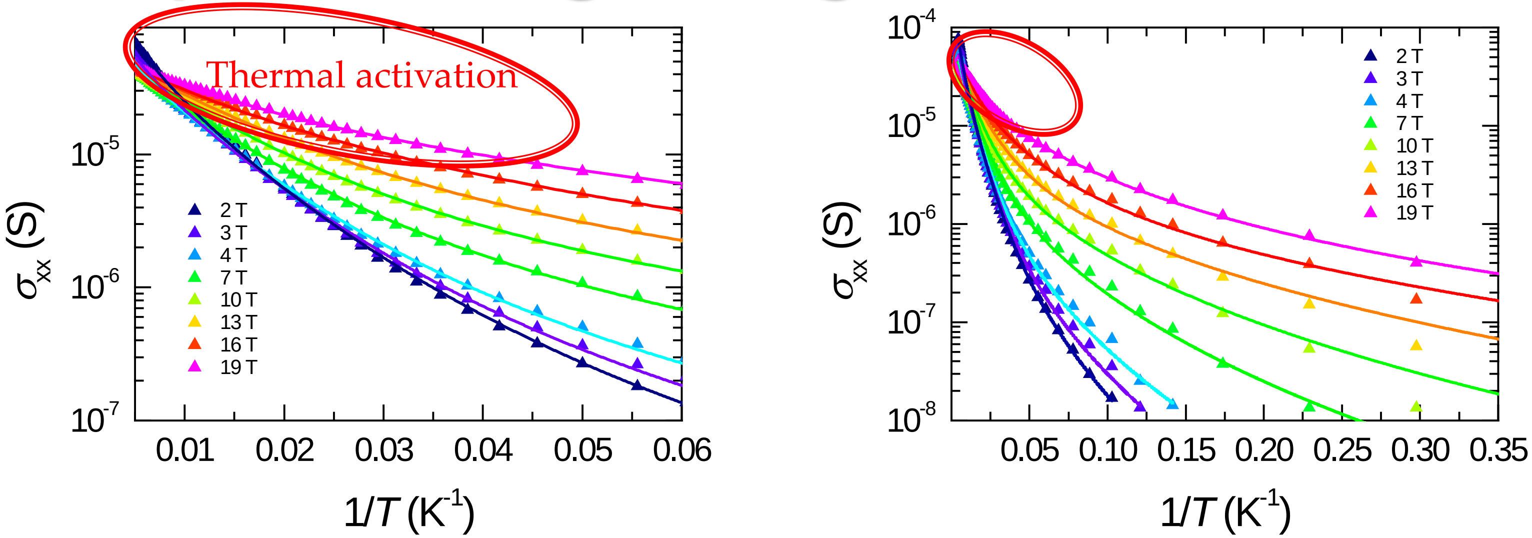




Longitudinal conductivity:
Variable range hopping (VRH) +
Thermal activation (TA) between
Landau levels



Temperature-dependent Magneto-transport in High Magnetic Fields



- Mott variable range hopping[1] (VRH) at low temperatures:

$$\sigma_{VRH} = \sigma_0 \cdot \exp[-(\boldsymbol{T_0}/_{T})^{\frac{1}{3}}]$$

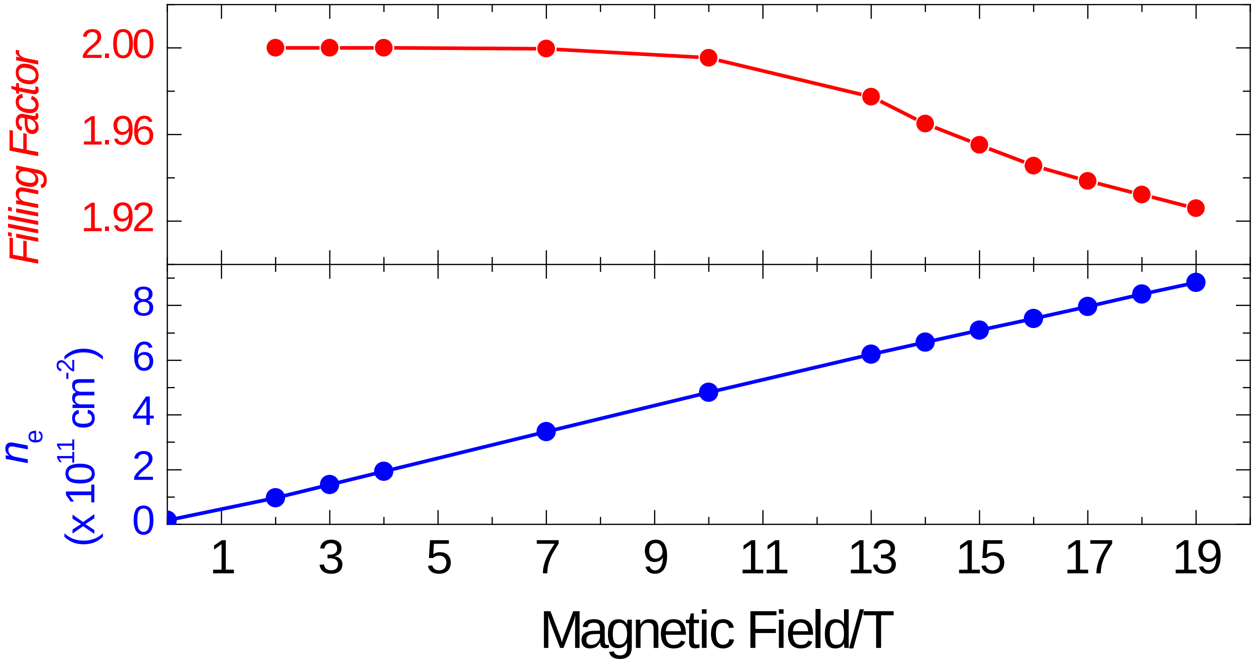
- Thermal activation[2,3] (TA) at high temperatures:

$$\sigma_{TA} = \frac{8e^2}{\pi h} \cdot [2e^{-\frac{\boldsymbol{E_F}}{kT}} + 4e^{-\frac{\boldsymbol{E_1}-\boldsymbol{E_F}}{kT}}] \cdot [\frac{kT}{\boldsymbol{\Gamma}} cosh \frac{\boldsymbol{\Gamma}}{kT} - (\frac{kT}{\boldsymbol{\Gamma}})^2 sinh \frac{\boldsymbol{\Gamma}}{kT}]$$

- Total conductivity: $\sigma_{xx} = \sigma_{VRH} + \sigma_{TA}$

1. **Mott**, J. Non-Crystal. Solid **1**, 1 (1968)
2. **Nicholas, Stradling,** and **Tidey**, Sol. State Commun. **23**, 341 (1977)
3. **Shon and Ando**, JPSC **67**, 2421 (1998)

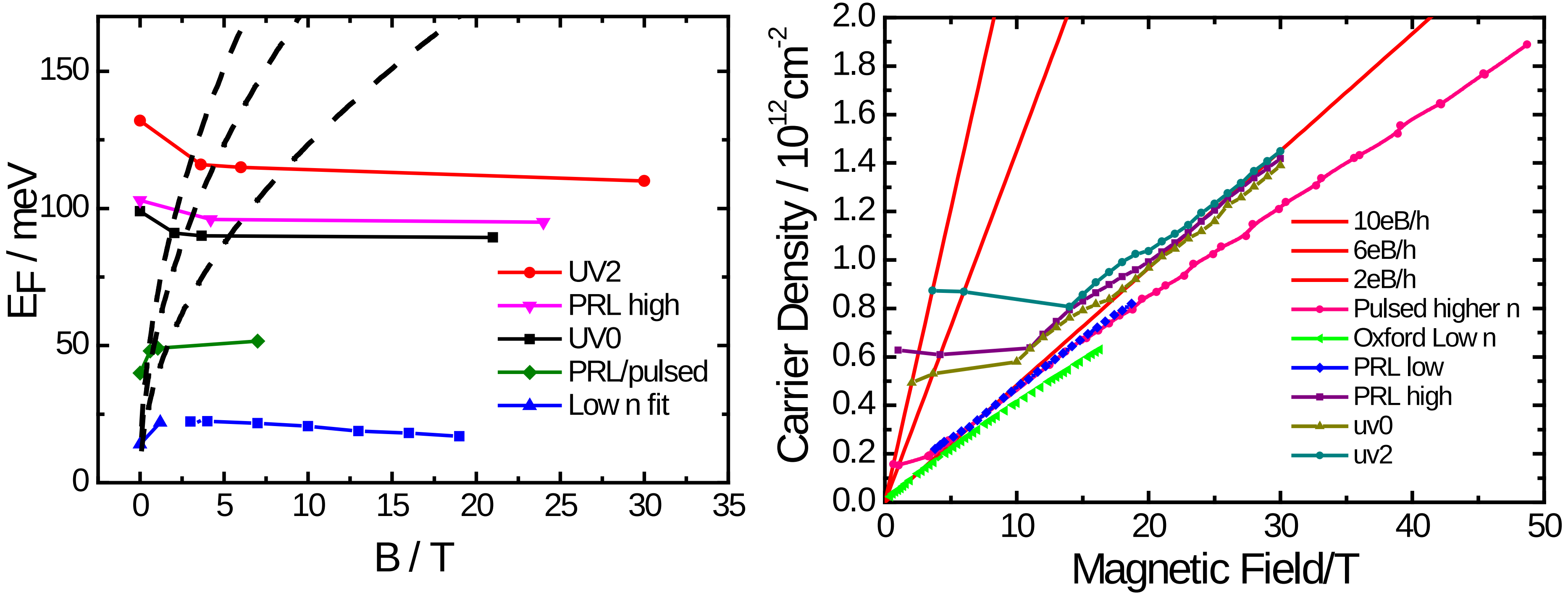
Filling Factor and Carrier Density



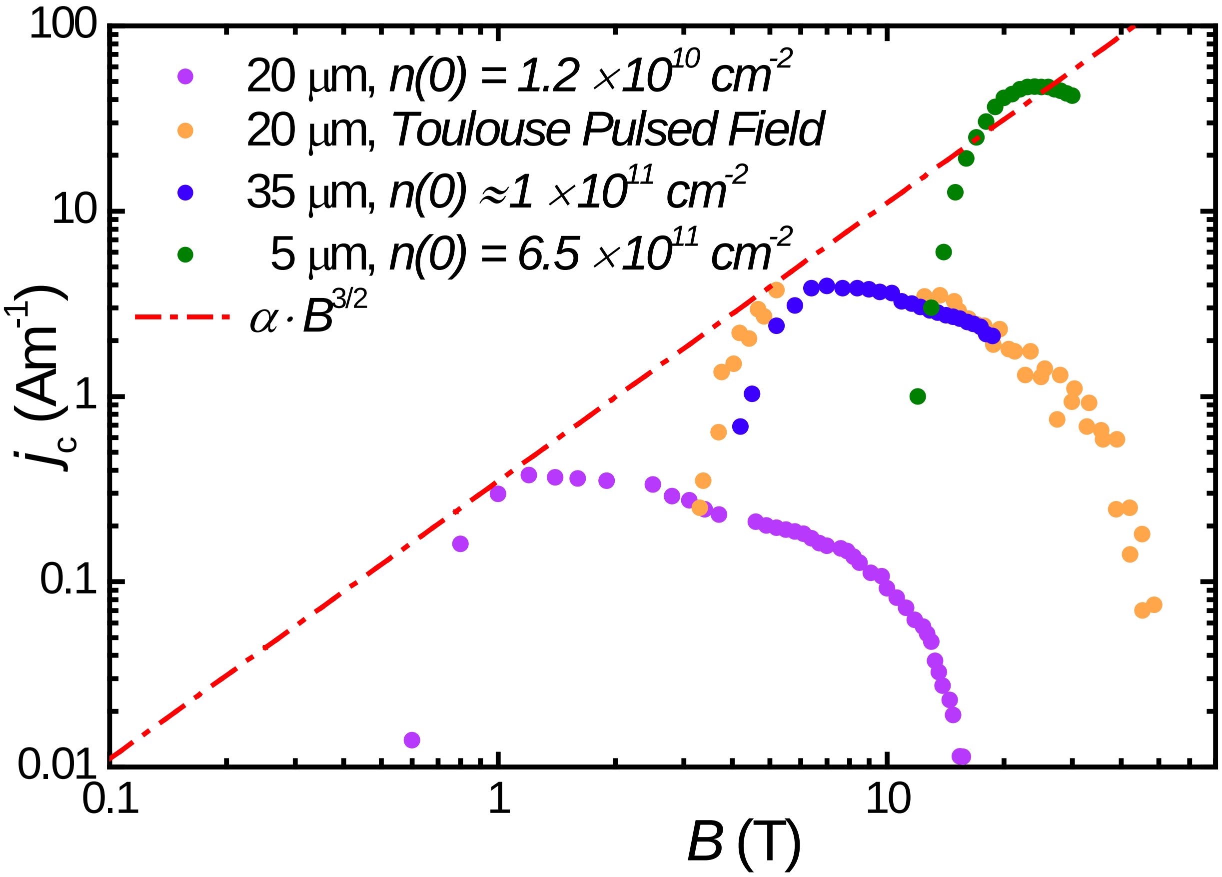
- Fermi level moves up the tail of the Gaussian LL0 as *B* increases: filling factor *υ* begins to decrease

- Nearly linear (sub-linear) magnetic field dependent charge transfer

Fermi energy is pinned



Magnetic Field Dependence of j_c

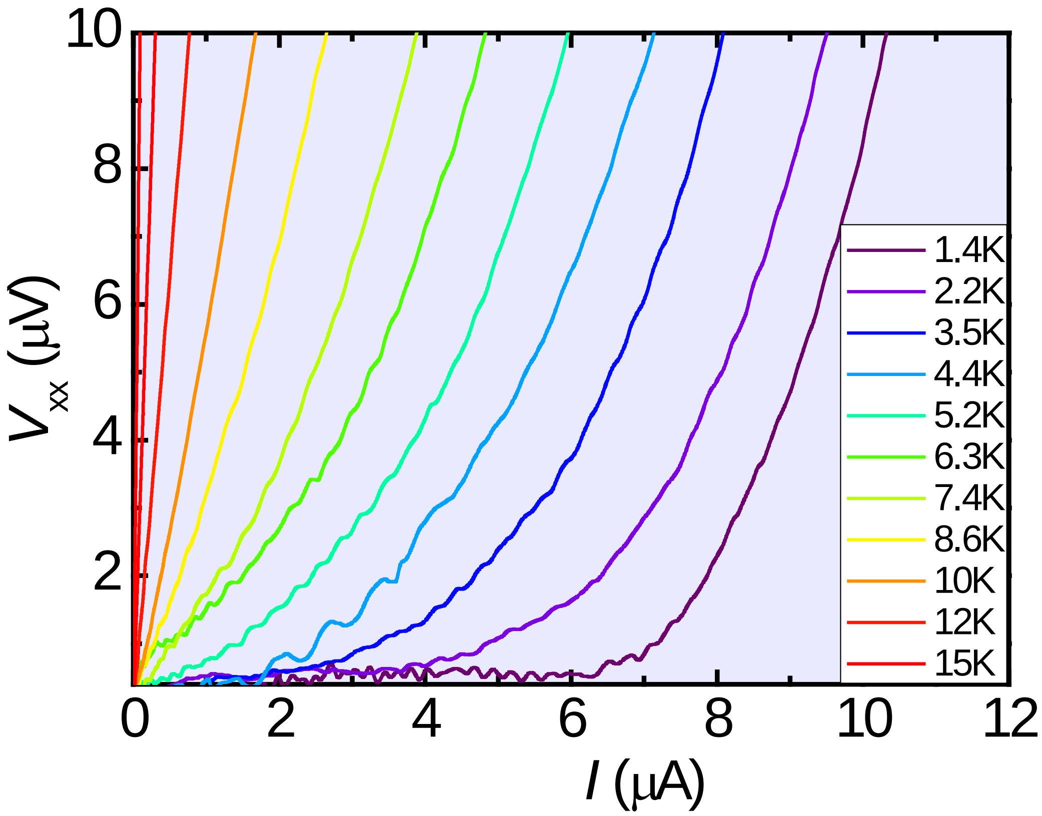


$B^{3/2}$ dependence – same as observed in GaAs

Peak j_c follows same behaviour as Tc

UV exposure may introduce inhomogeneities

Temperature dependent Breakdown of QHE



Low field plateau at 1.2 T

n~1.5x10^{10} cm^{-2}

I_c @ Vxx=1 μV
ρxx<0.1Ω

Over 7 μA in 20μm wide device at 2K

J_c = 0.35A/m comparable to GaAs at 5T

Temperature Dependence

Temperature dependence common to traditional semiconductor 2DEGs [1,2]

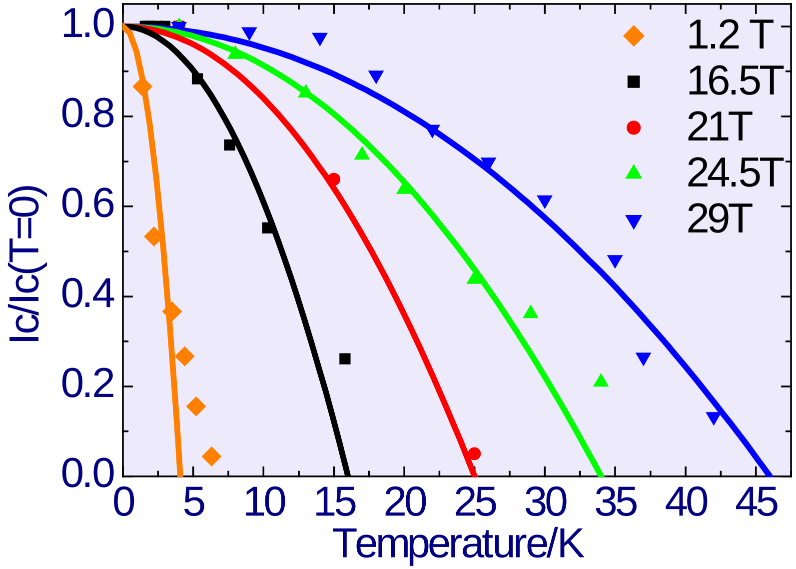
$$Ic(T) \propto \left(1 - \frac{T^2}{T_c^2}\right)$$

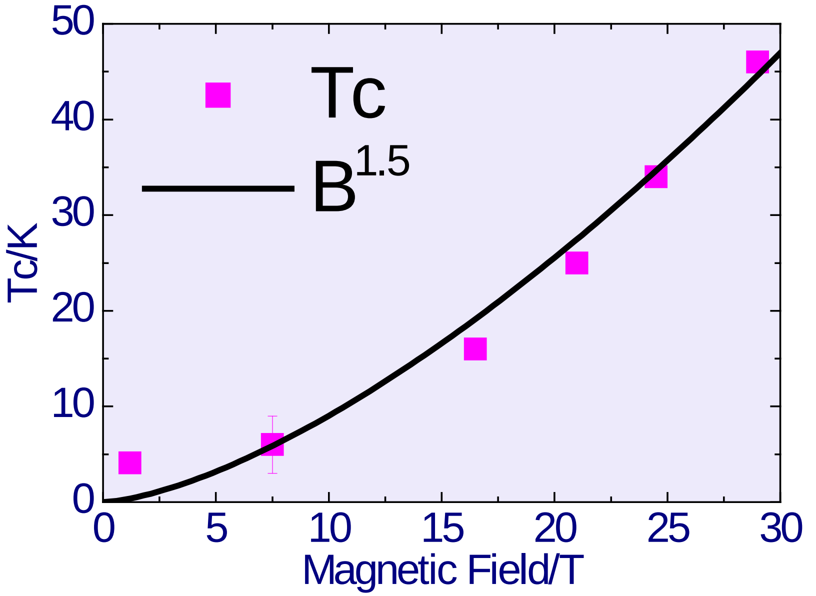
Superlinear dependence on B

$\hbar\omega_c \sim B^{1/2}$ – Disorder broadening LL

Predicts Tc~85K at 45T for <u>dissipationless</u> state

[1] L.B. Rigal et al., PRL 82, 1249 (1999)
[2] H. Tanaka, et al. JPSJ 75, 014701 (2006)





Boostrap Electon Heating Model

Komiyama and Kawaguchi, PRB 61 2014 (2000)

- At breakdown:

Rate of change of energy input > Rate of change of energy loss

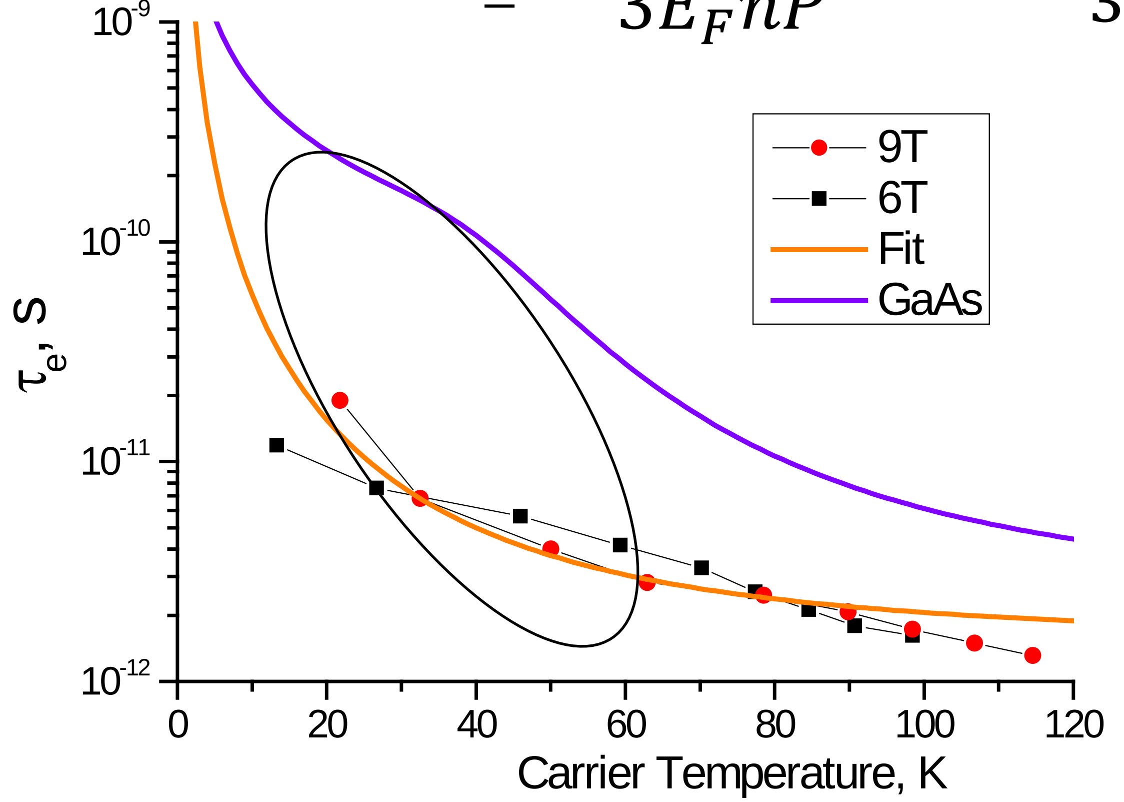
$$E_b = \sqrt{{}^{4B\hbar\omega_c}/_{\eta e\tau_e}}$$

Degeneracy, η = 4 for graphene

- Depends on cyclotron energy and energy loss time, τ_e
- Overestimates breakdown current by a factor of ~2 in best GaAs devices
- Upper limit for breakdown current

Energy relaxation Lifetime

$$\tau_e = \frac{\pi^2 {k_B}^2 {T_e}^2}{3E_F nP} = \frac{\pi^2 {k_B}^2 {T_e}^2}{3E_F \alpha T^4} + \tau_0$$

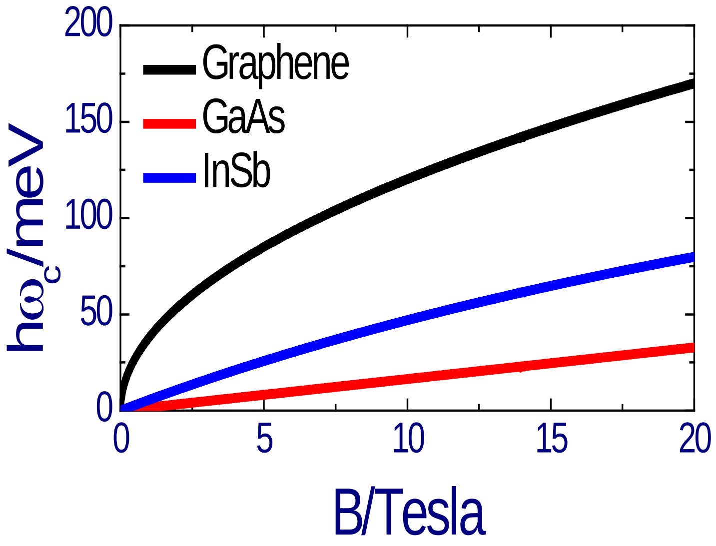


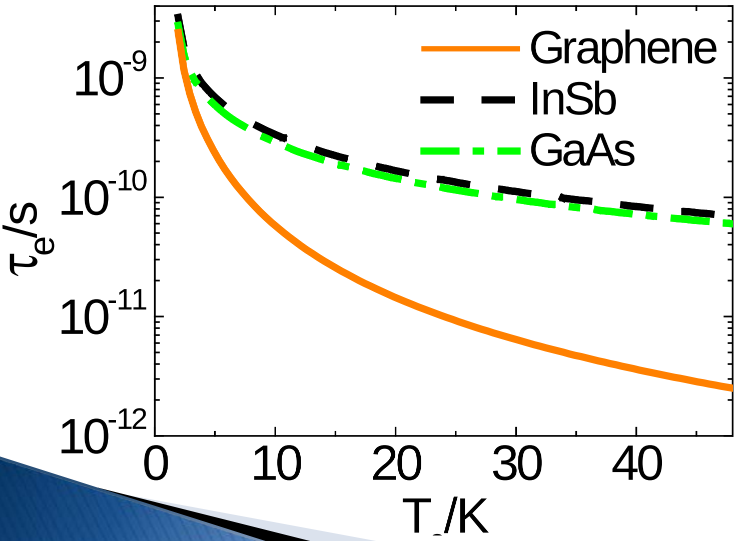
τ_e - GaAs (100ps)

τ_e - graphene (100-5ps)

A.M.R. Baker et al, PRB 85, 115403 (2012)
A.M.R. Baker et al., PRB 87, 045414 (2013)

Material Dependence





Material	$\hbar\omega_c$ (meV)	τ_e (ps)	Tc (K)	Jc (theory)	Jc (exp) (A/m)
GaAs (7T)	12	100	7	2.9	1.4[1]
InSb (7T)	40	500	9	2.6	0.3[2]
Graphene (1.2T)	42	500	4	0.7	0.35
(7T)	105	80	10	7.3	4.3
(16T)	165	16	16	36	30
(23T)	200	6	34	71	43

$$E_b = \sqrt{4B\hbar\omega_c/\eta e\tau_e}$$

[1] H. Tanaka, et al. JPSJ 75, 014701 (2006)
[2] JA-W. et al. PRB 86, 045404 (2012)
Komiyama and Kawaguchi, PRB 61 2014 (2000)
Baker, JA-W et al., PRB 85, 115403 (2012)
Baker, JA-W et al., PRB 87, 045414 (2013)

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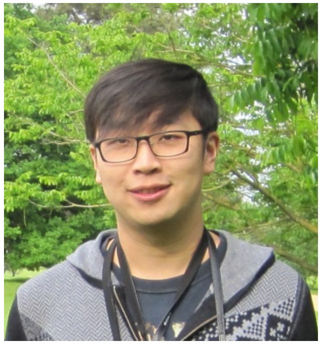

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JT Janssen, Alexander Tzalenchuk

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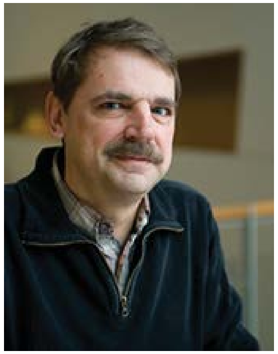
Thomas Yager, Samuel Lara-Avila, Sergey Kubatkin



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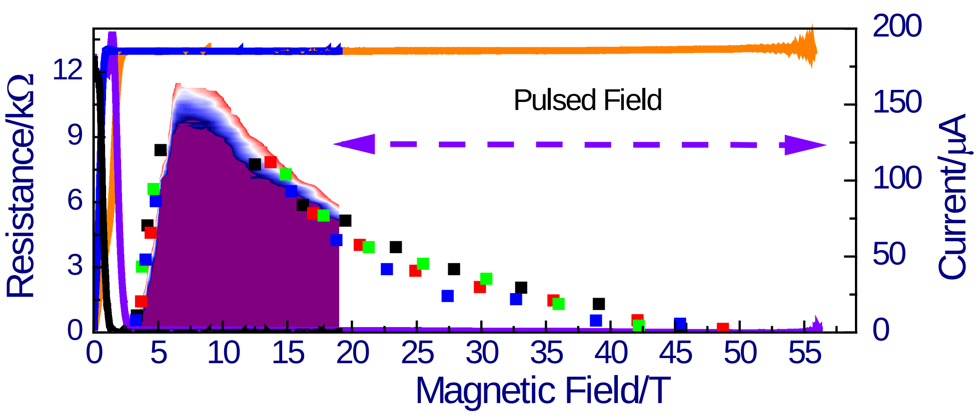
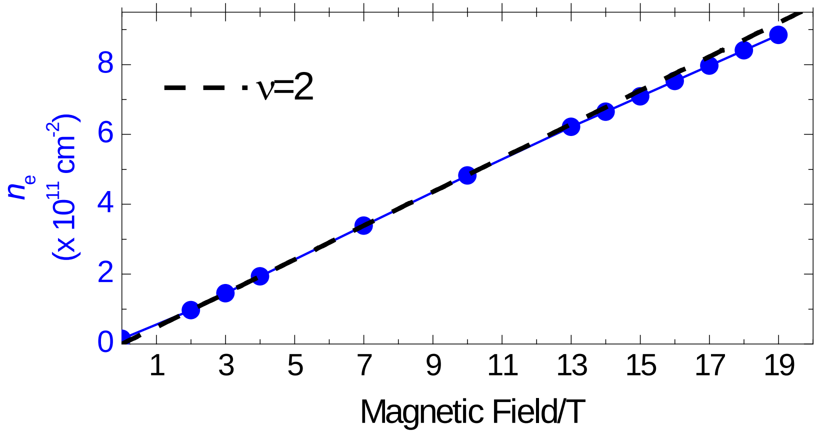
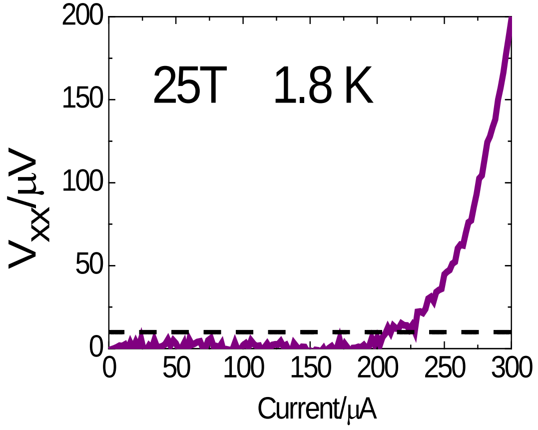
Summary

Strongly magnetic field dependent carrier density





Very high critical currents, Superlinear dep. of j_c and T_c on B



$$Jc = 43\text{A/m} \ @\ 23\text{T}$$

$$Tc = 45\text{K} \ @\ 29\text{T}$$

$$Ic(T) \propto \left(1 - \frac{T^2}{T_c^2}\right)$$