Exceptional service in the national interest

Sandia National Laboratories

Quantum Hall Effect in Vanishing Magnetic Fields

Wei Pan
Sandia National Labs

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia is a multi-mission laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

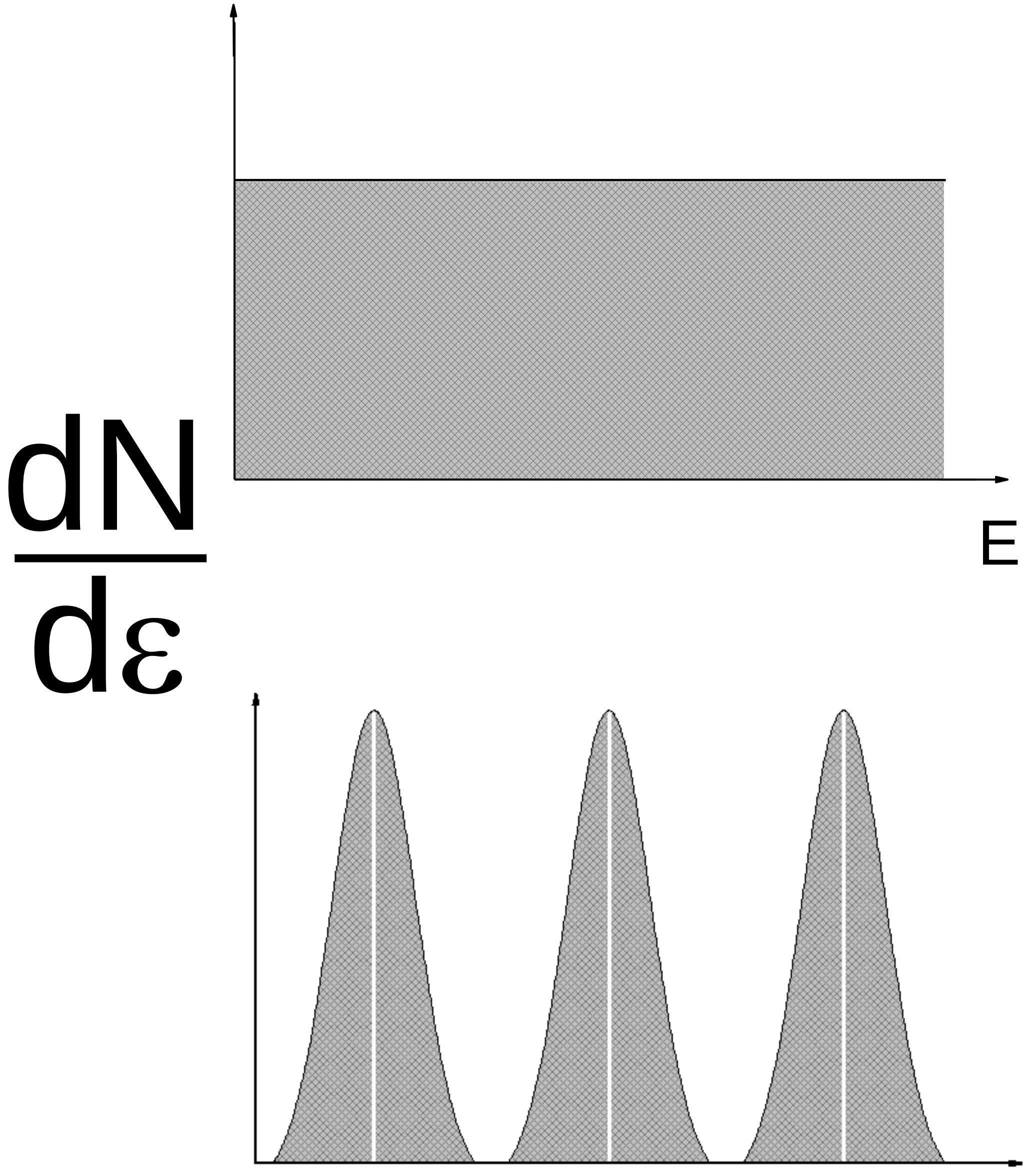
U.S. DEPARTMENT OF ENERGY | Office of Science

Part I: Anti-levitation of Landau levels in vanishing magnetic fields (Pan et al, PRB (2016))

Part II: Collapse of spin splitting in the quantum Hall regime (Pan et al, PRB (2011))

part I outline

- Background
- Sample
  - HIGFET (**H**eterojunction **I**nsulated-**G**ate **F**ield-**E**ffect **T**ransistor)
- Results
  - Anti-levitation is observed at low Landau level fillings ν=4,5,6.
  - This observation is in good agreement with a recent theoretical prediction (C. Wang et al, PRB **89**, 045314 (2014)).

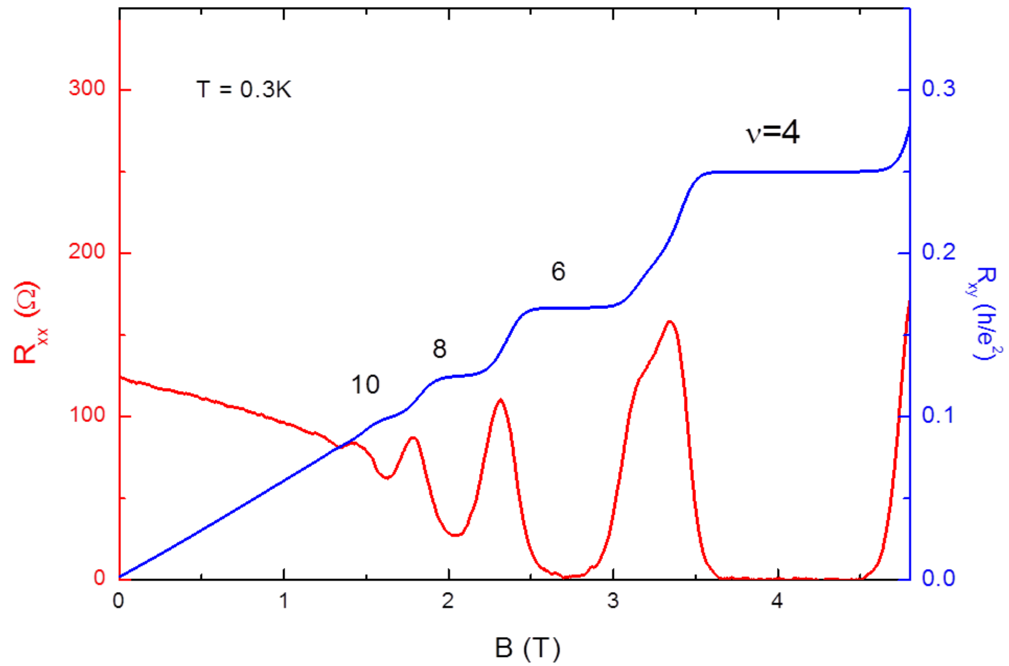


B = 0

B ≠ 0

$E = (N+1/2)\hbar\omega_c$

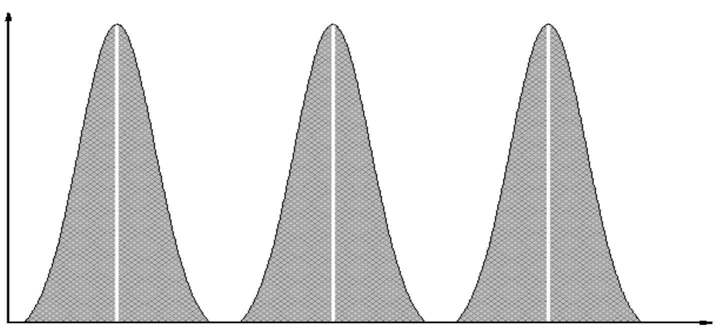
Integer quantum Hall effect



R_{xy} quantized

$$R_{xy} = \frac{h}{\nu e^2}$$

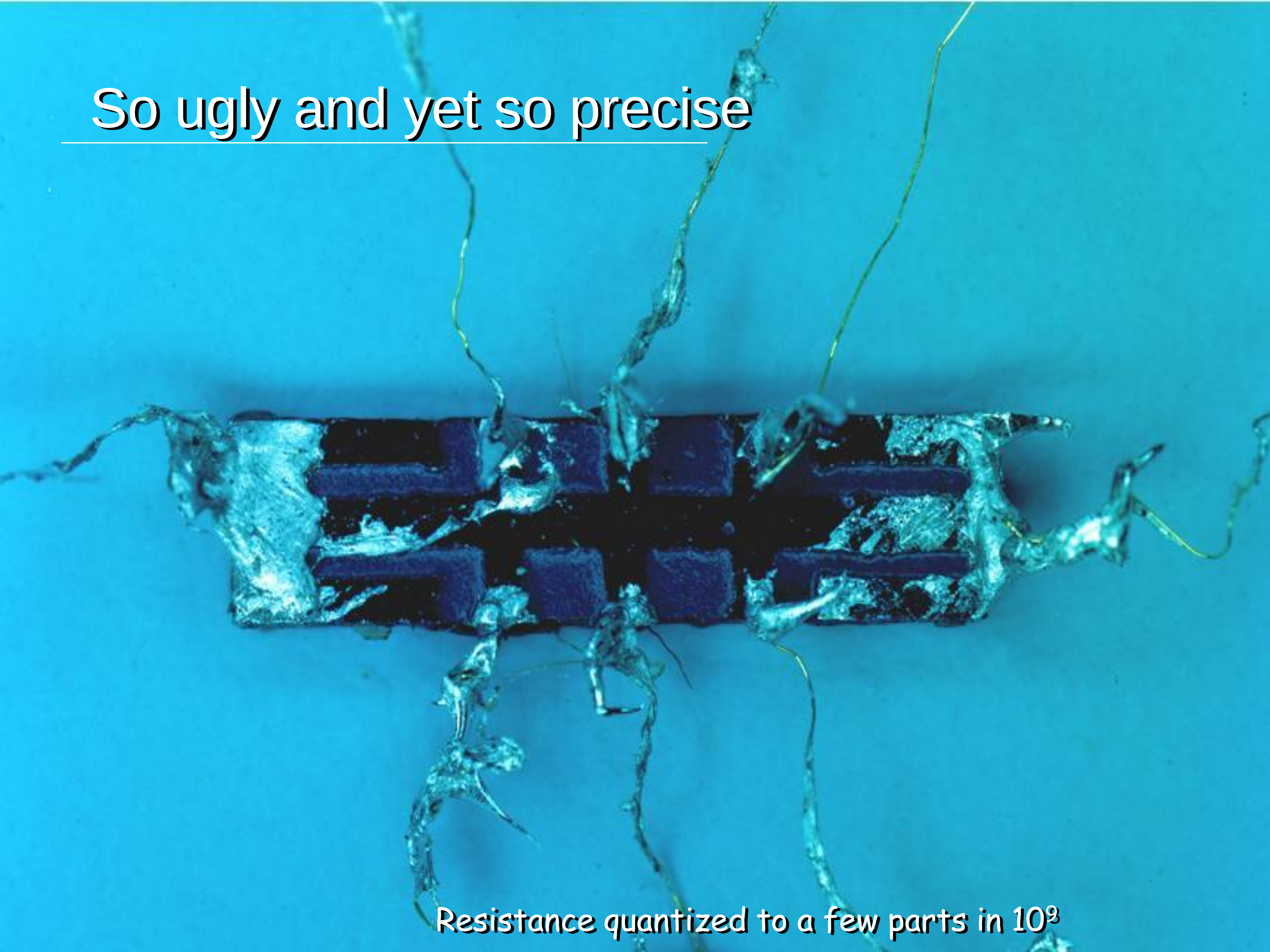
R_{xx} zero



ν – Landau level filling

ν = nh/eB (n density)

So ugly and yet so precise



Resistance quantized to a few parts in 10^9

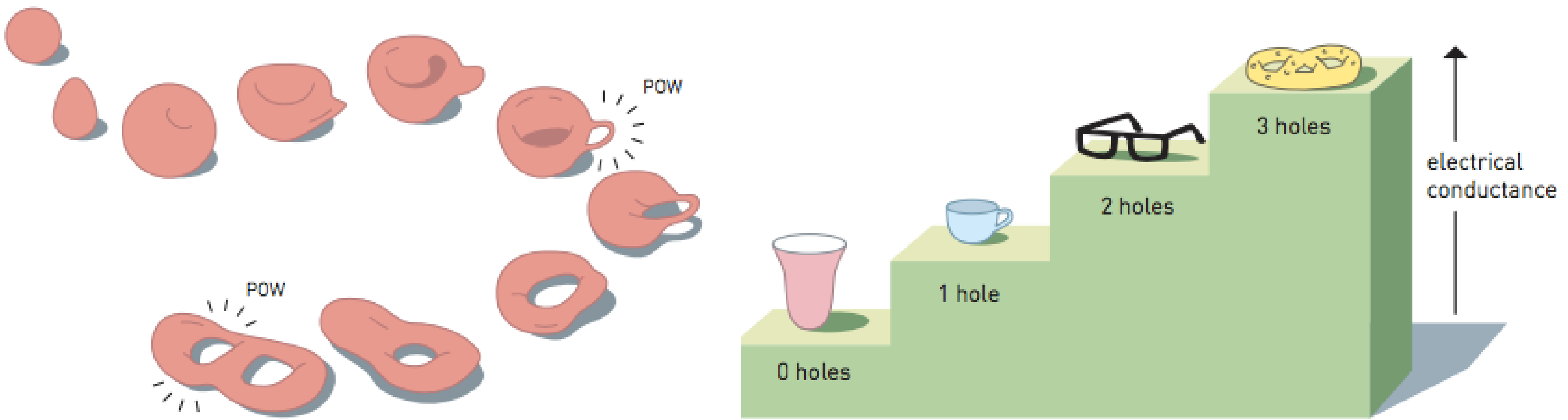


Fig 3. Topology. This branch of mathematics is interested in properties that change step-wise, like the number of holes in the above objects. Topology was the key to the Nobel Laureates' discoveries, and it explains why electrical conductivity inside thin layers changes in integer steps.

(source: www.nobelprize.org)

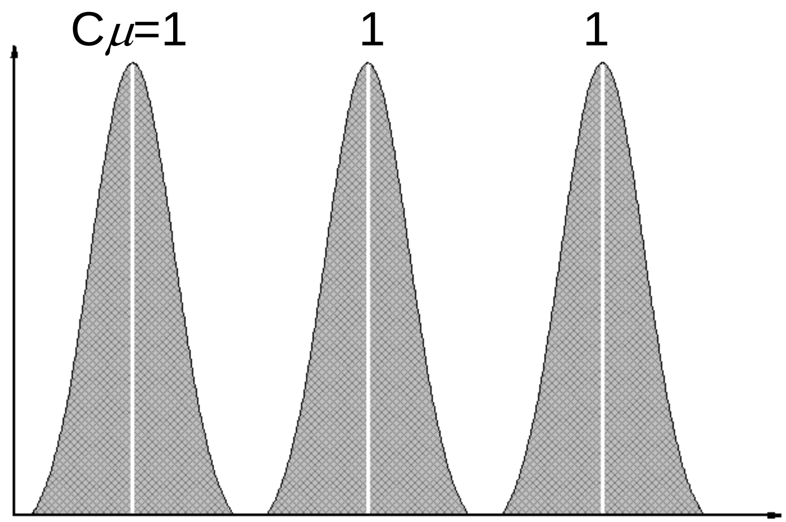
Chern number as a topological order parameter: TKNN formula

$$\sigma_{xy} \propto \int_{\mathbf{k}\in \mathrm{BZ}} d^2\mathbf{k} \sum_{\epsilon_\mu(\mathbf{k})<\epsilon_F<\epsilon_\nu(\mathbf{k})} \frac{\langle u_\mu(\mathbf{k})|\nabla_{\mathbf{k}} H}{}$$

$$= \int_{\mathbf{k}\in \mathrm{BZ}} d^2\mathbf{k} \sum_{\epsilon_\mu(\mathbf{k})<\epsilon_F} \langle \nabla_{\mathbf{k}} u_\mu(\mathbf{k})| \times |\nabla_{\mathbf{k}} u_\mu$$

where $u_{\mu\mathbf{k}}(\mathbf{r})$ is the periodic part of a Bloch wave fun

$$\left[\frac{1}{2m}\left(-i\hbar\nabla + i\right.\right.$$



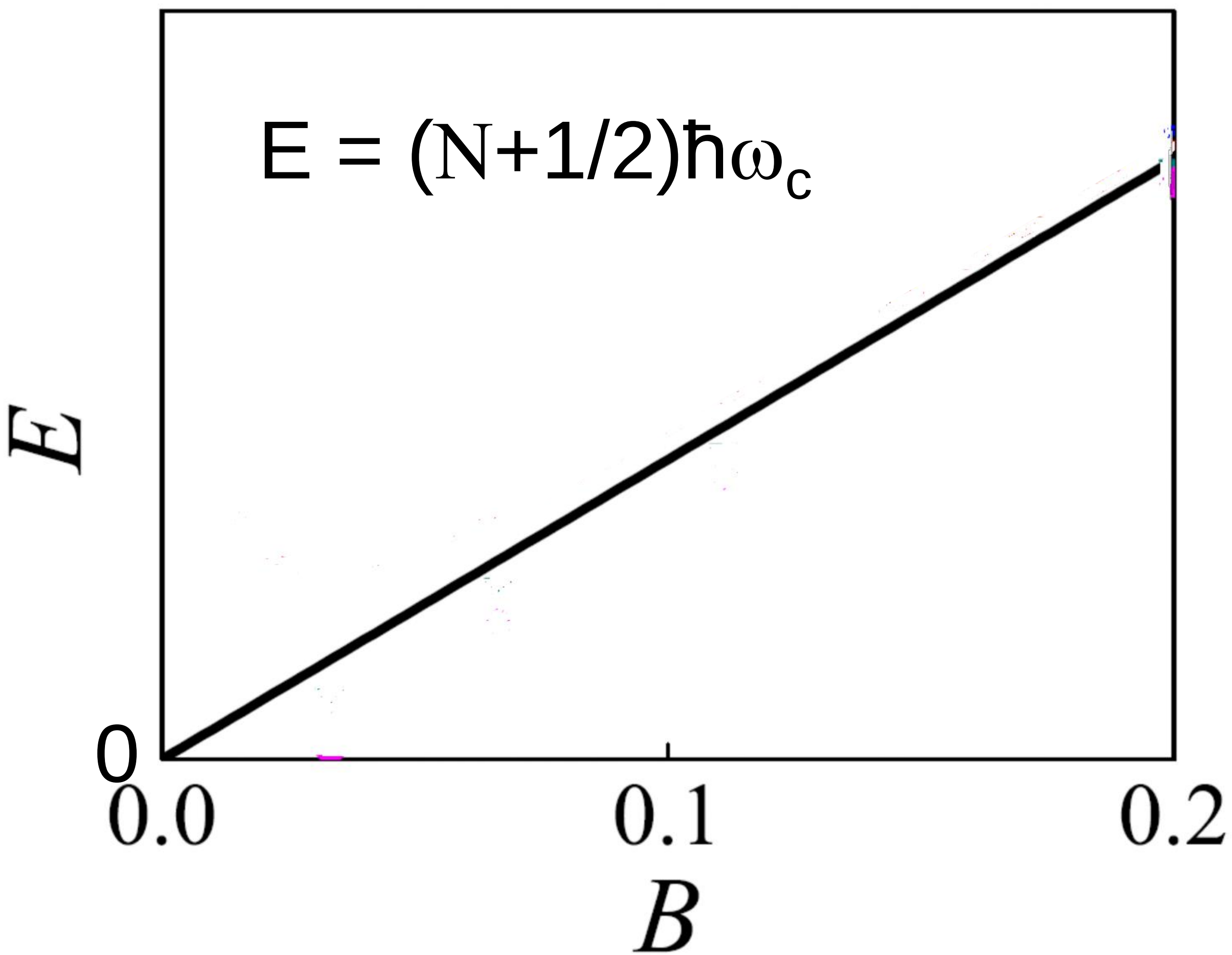
- This is the famous Thouless-Kohmoto-Night
the topologically invariant "order parameter" c
conductivity via $\sigma_{xy}=ne^2/h$.

$$n = \sum_{\epsilon_\mu(\mathbf{k})<\epsilon_F} \mathcal{C}_\mu$$

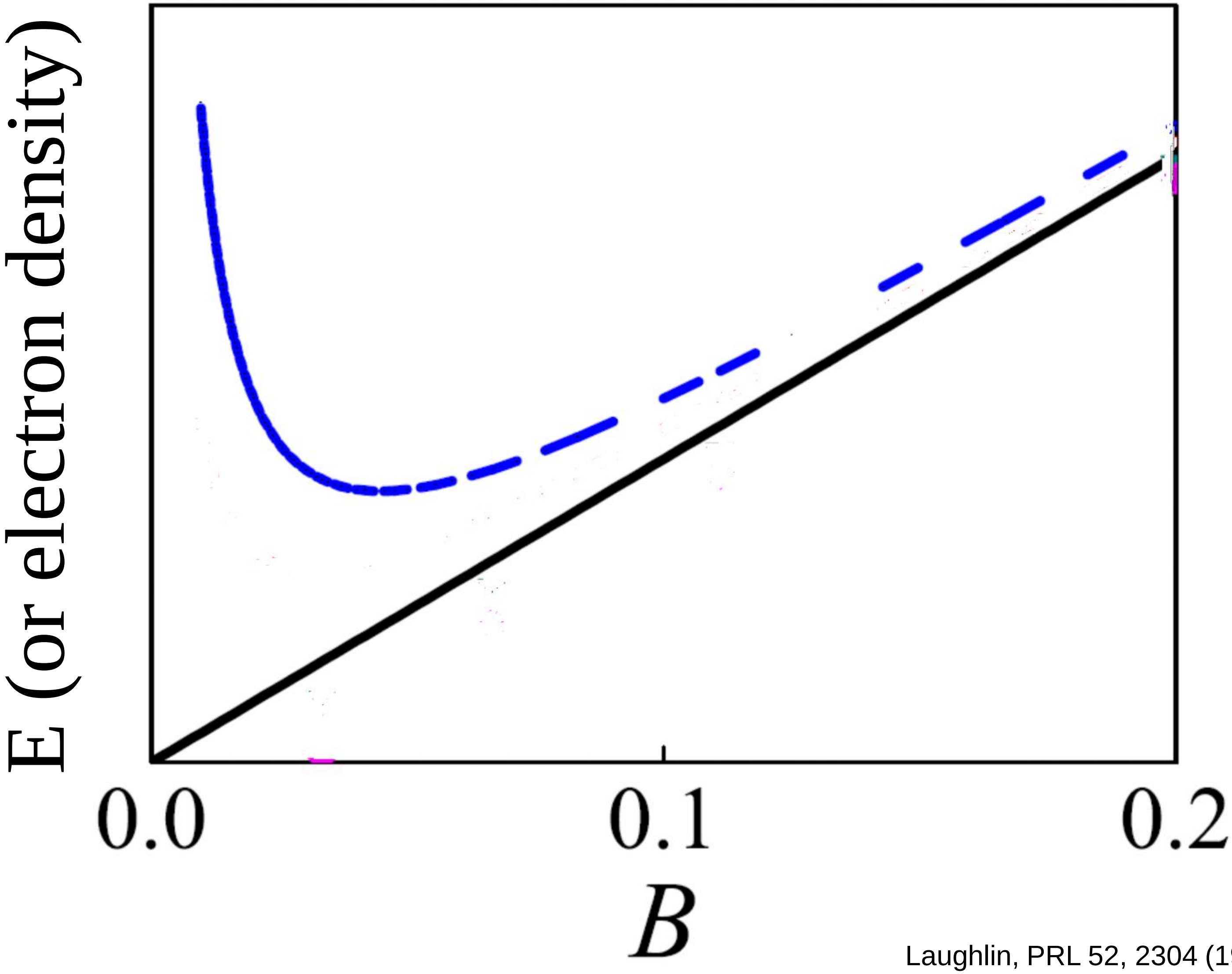
$$\boxed{\mathcal{C}_\mu = \frac{i}{2\pi}\int_{\mathbf{k}\in \mathrm{BZ}} d^2\mathbf{k} \langle \nabla_{\mathbf{k}} u_\mu(\mathbf{k})| \times |\nabla_{\mathbf{k}} u_\mu(\mathbf{k})\rangle \cdot \hat{z}}$$

(by Kwon Park)

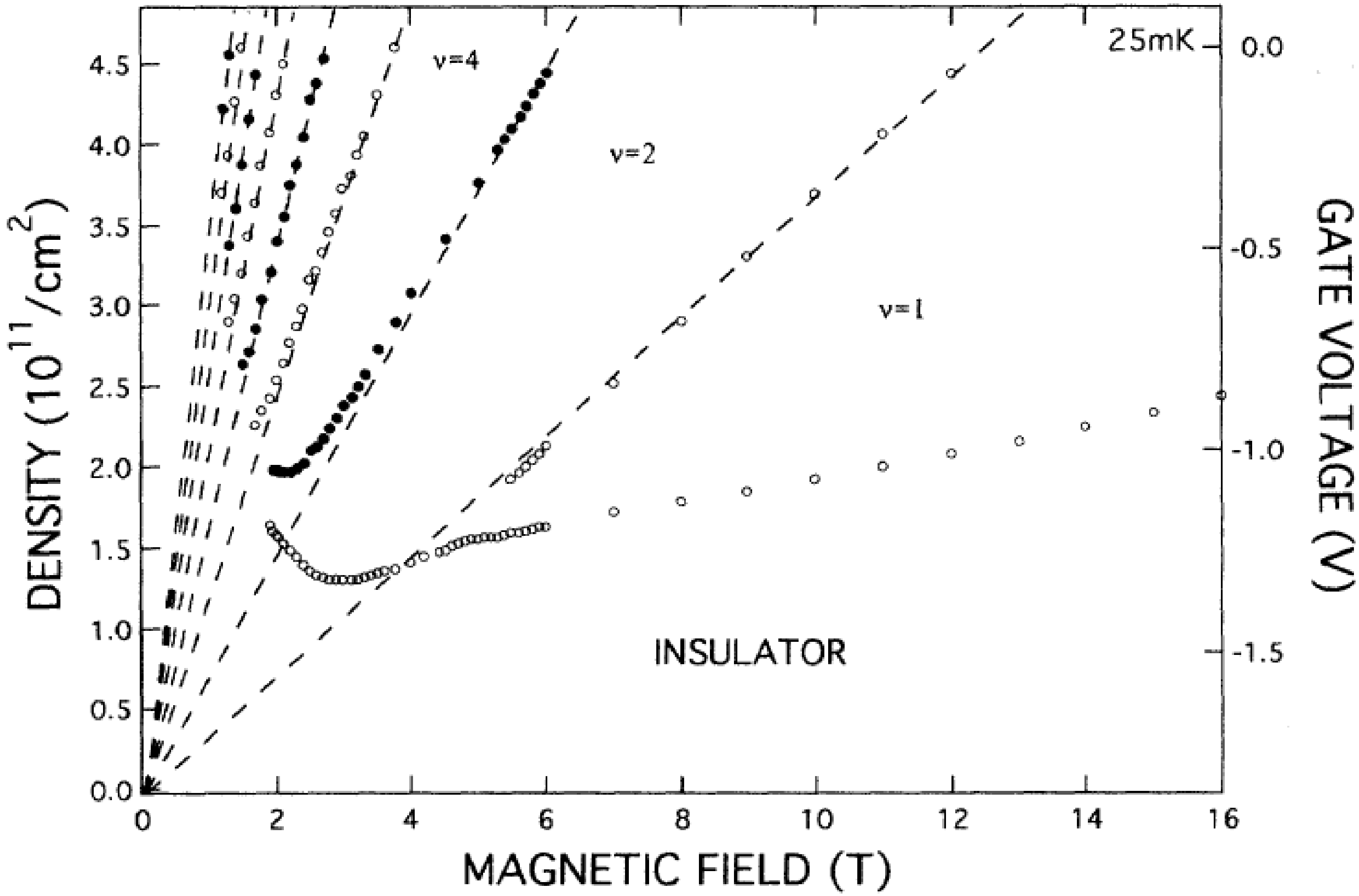
Chern number never disappears by itself



Floating of Landau levels in vanishing B field



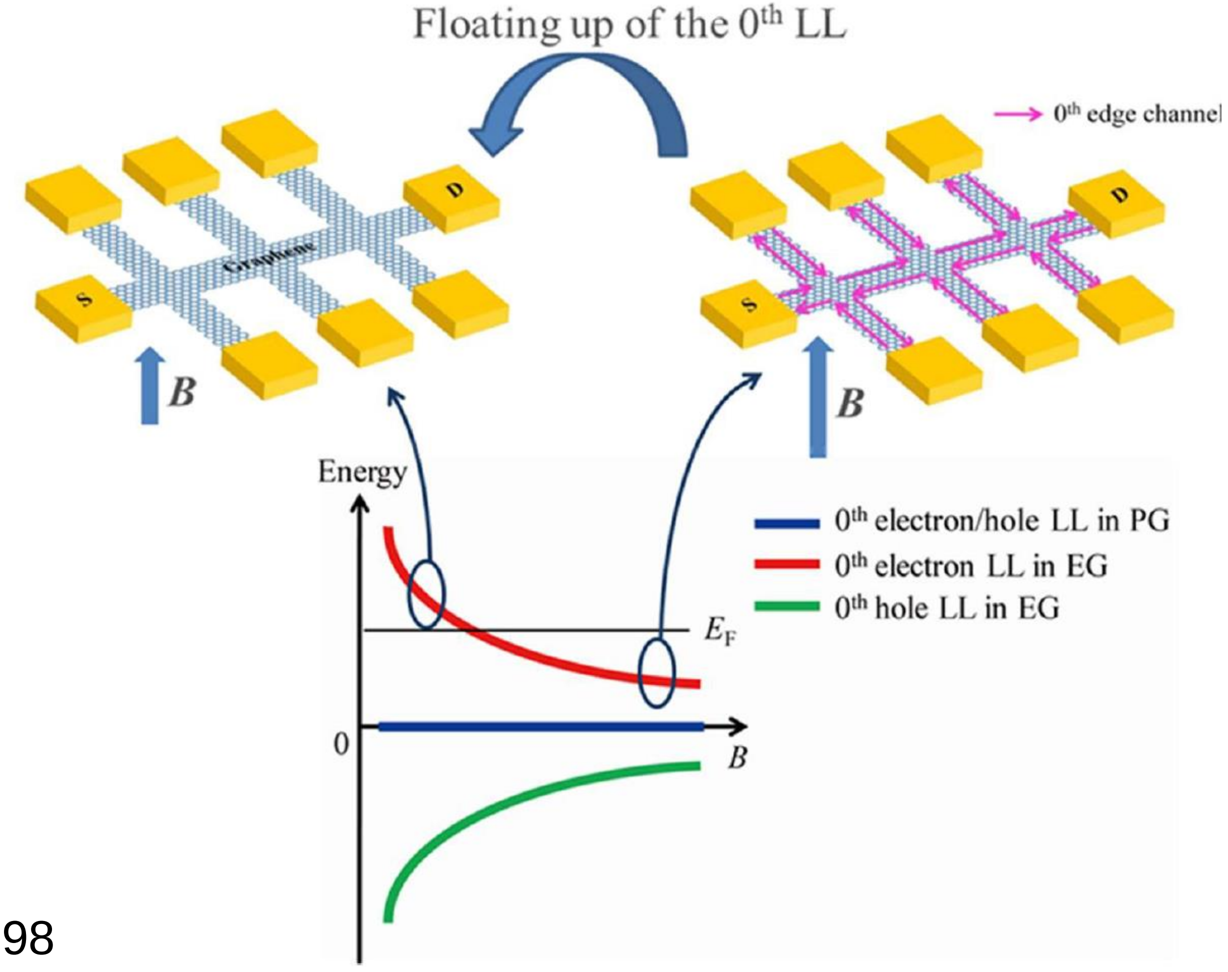
Laughlin, PRL 52, 2304 (1984).
Khmelnitskii, Phys. Lett. A 106, 182 (1984).



Glozman, Johnson, and Jiang PRL 74, 594 (1995)

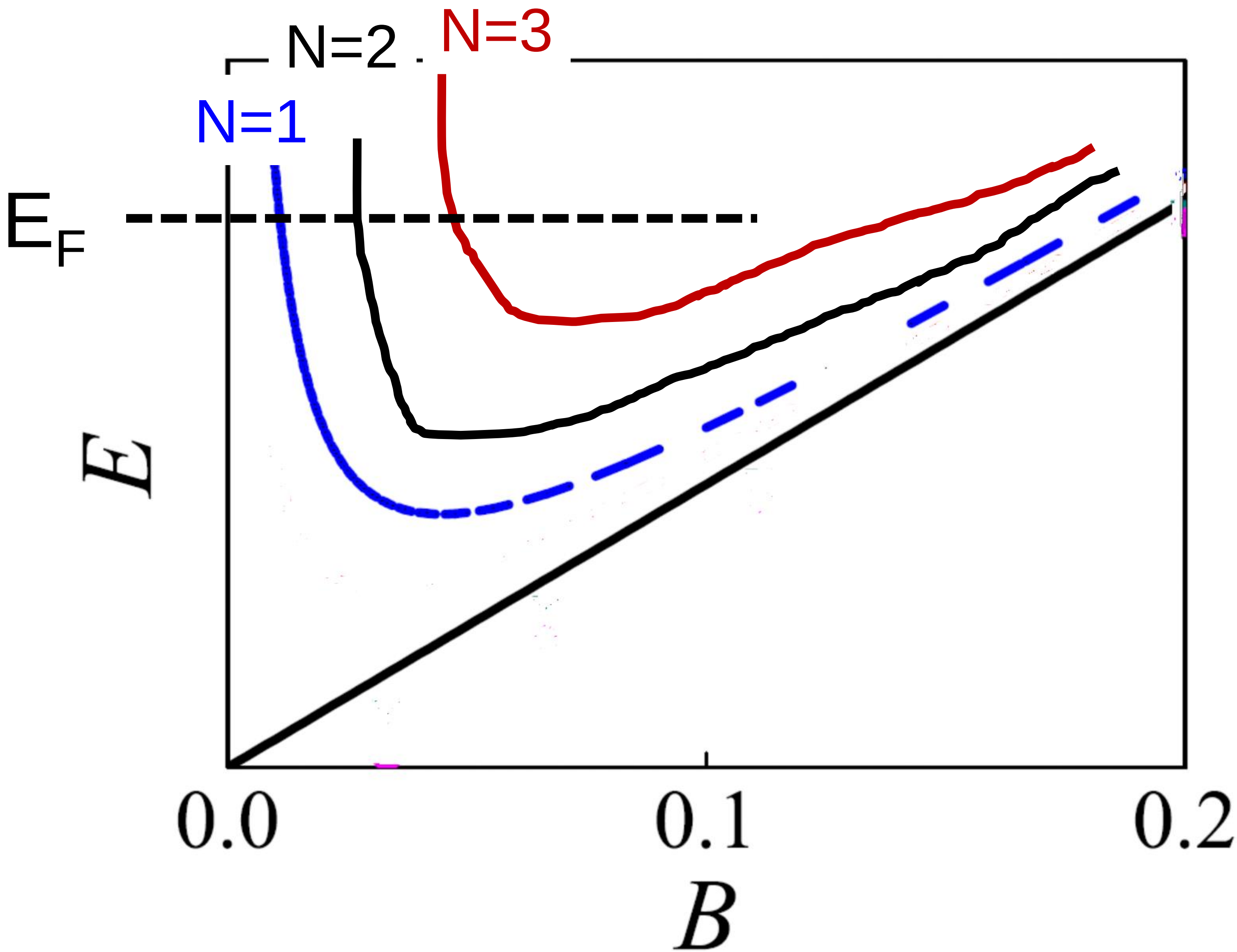
Floating up of the zero-energy Landau level in monolayer epitaxial graphene

Lung-I Huang[1,2], Yanfei Yang[1,3], Randolph E. Elmquist[1],
Shun-Tsung Lo[4,*], Fan-Hung Liu[4], and Chi-Te Liang[2,4,*]

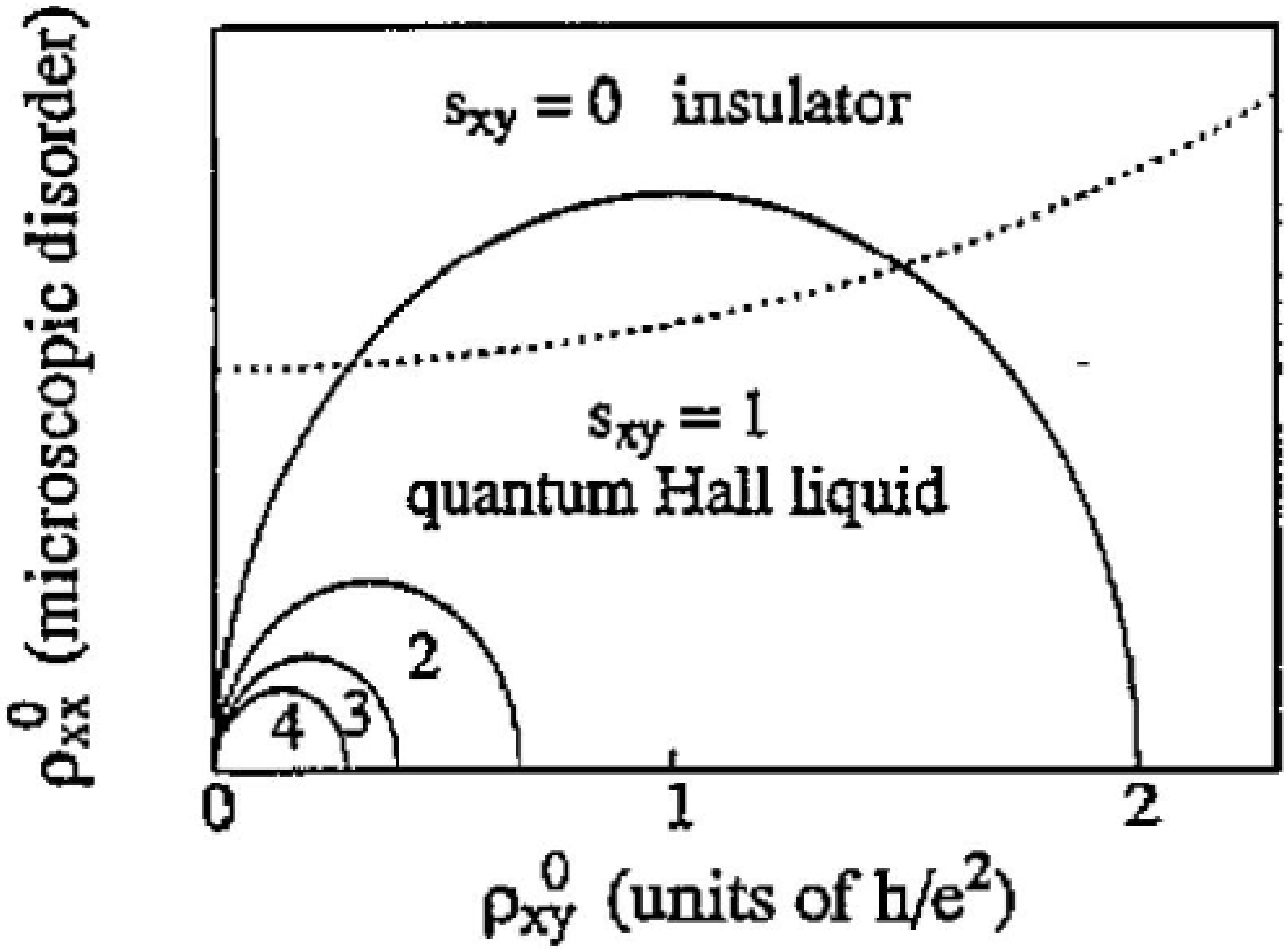


arXiv:1602.08198

Only insulator to N = 1 transition allowed



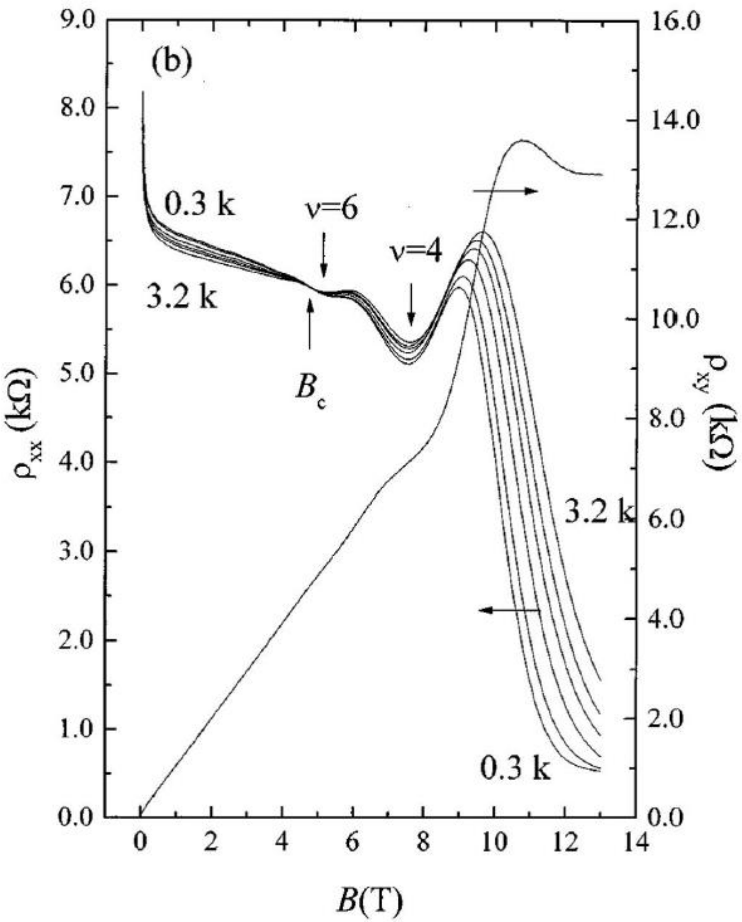
Global phase diagram



S.A. Kivelson, D.H. Lee, and S.C. Zhang, PRB (1992)

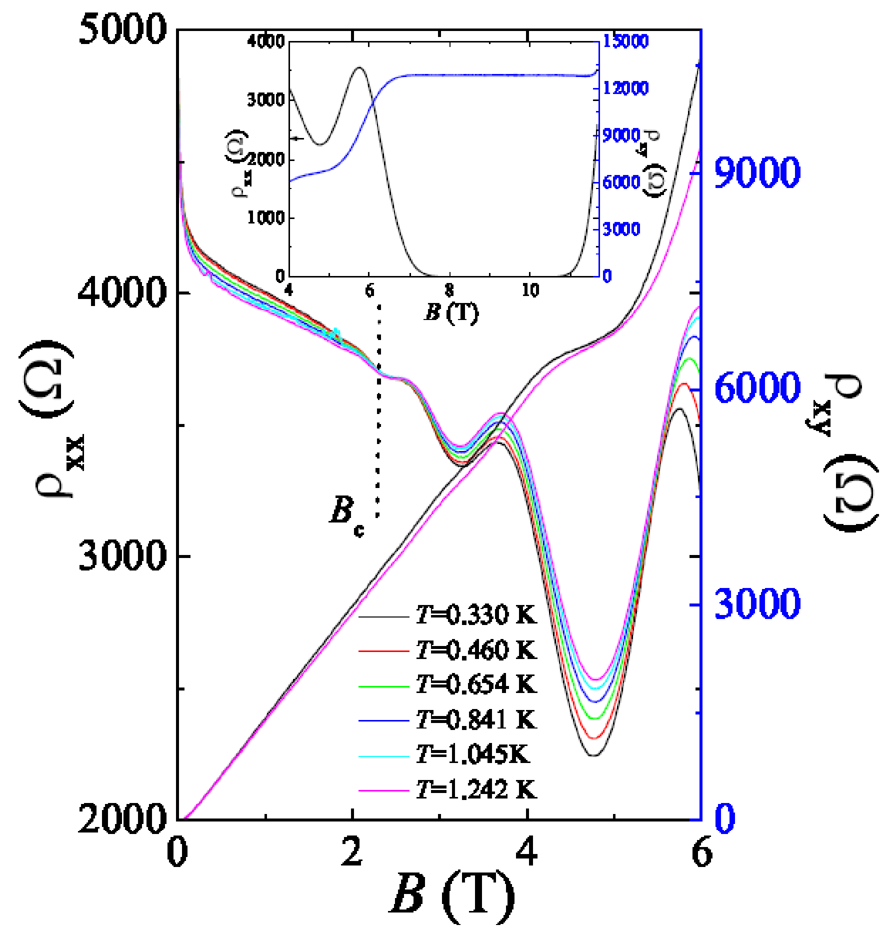
However, transition from insulator to high order quantum Hall states has been observed in experiments …

Insulator to N=3 transition



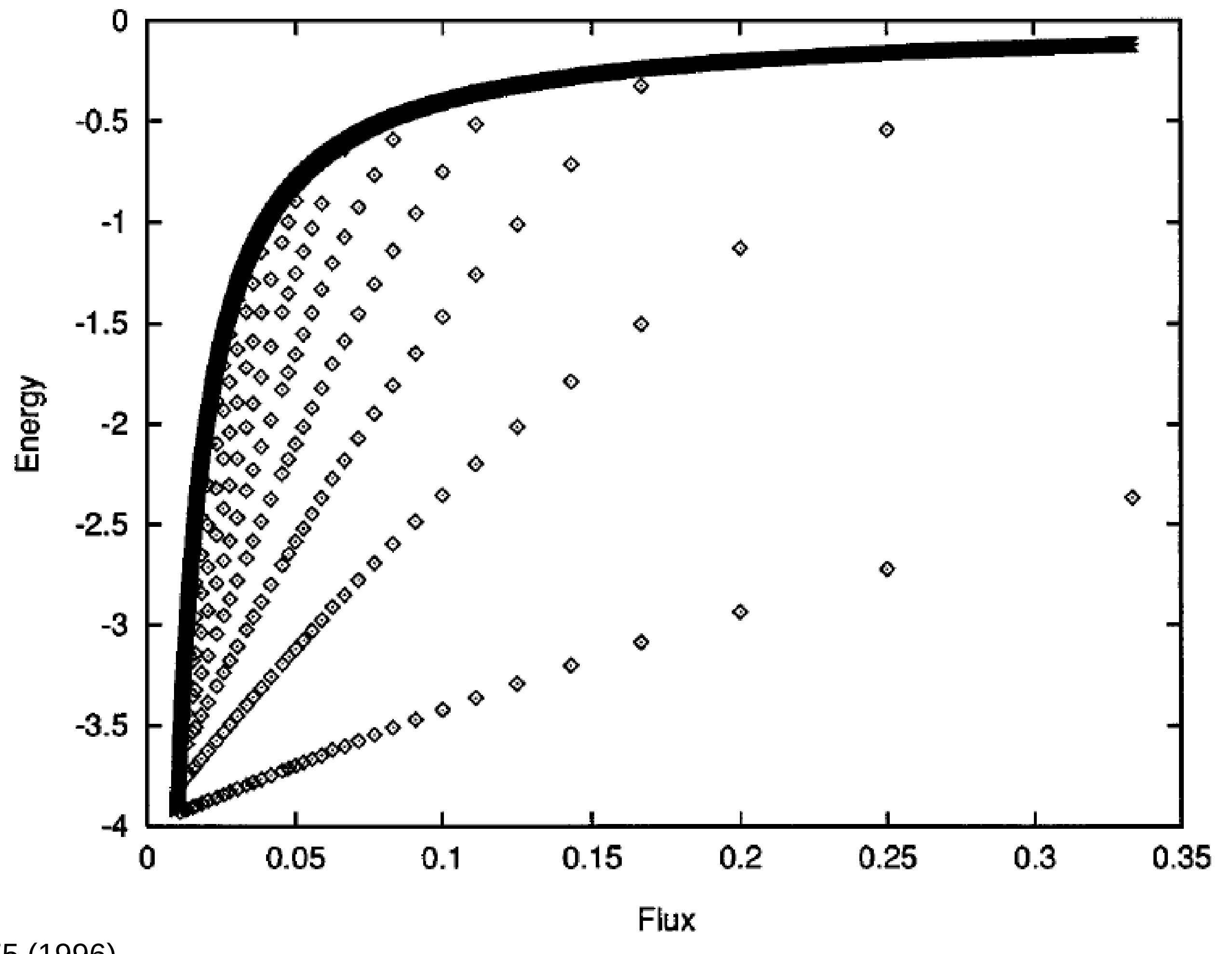
C.H. Lee, Y.H. Chang, Y.W. Suen, and H.H. Lin, PRB (1998)

Insulator to N=4 transition



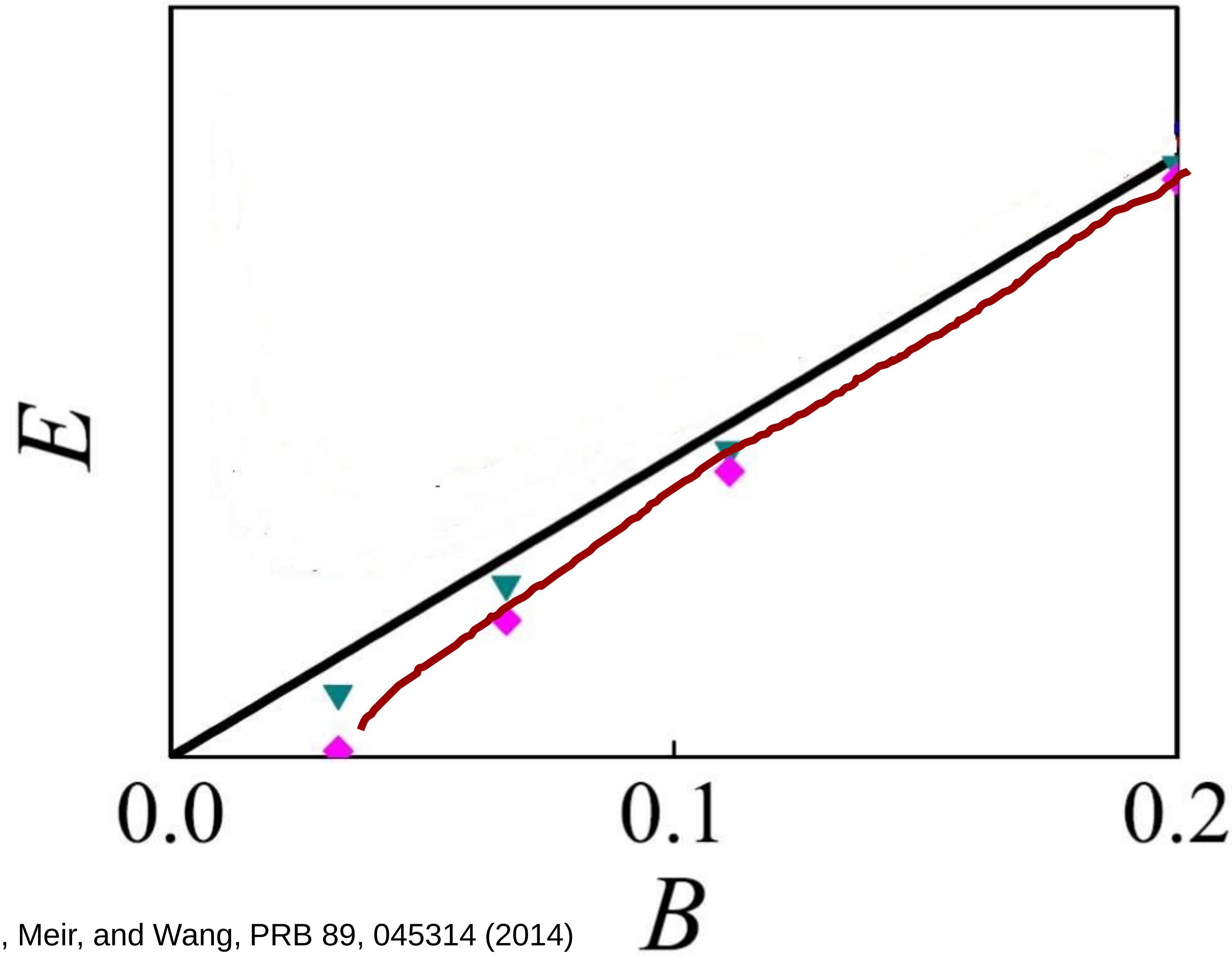
S.T. Lo, et al, C.-T. Liang, Solid State Commun. (2010)

non-floating behavior



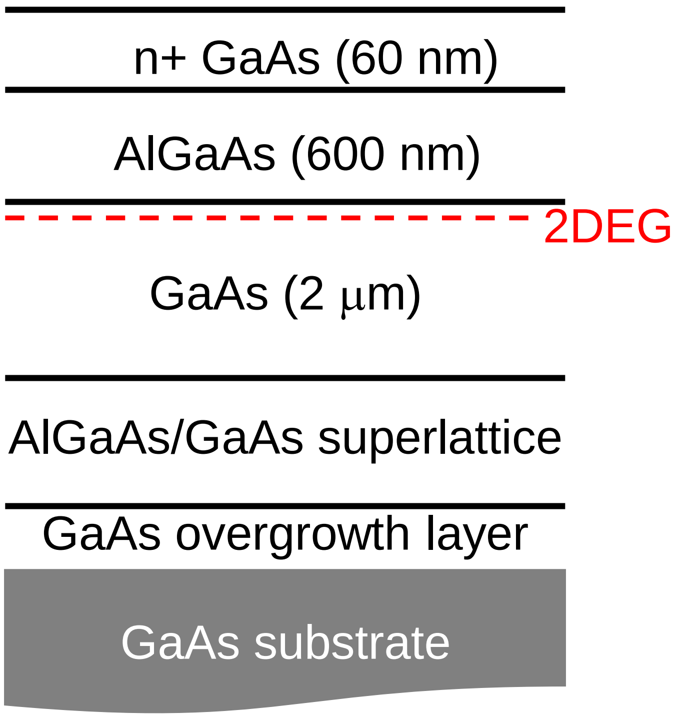
Liu et al, PRL 76, 975 (1996)
Sheng et al, PRL 78, 318 (1997)
Yang et al, PRL 76, 1316 (1996)

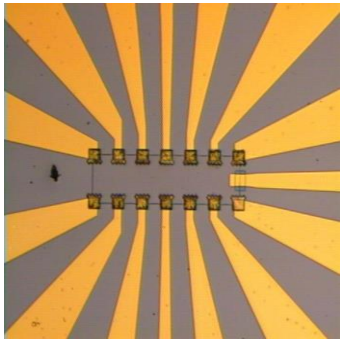
Anti-levitation of Landau levels

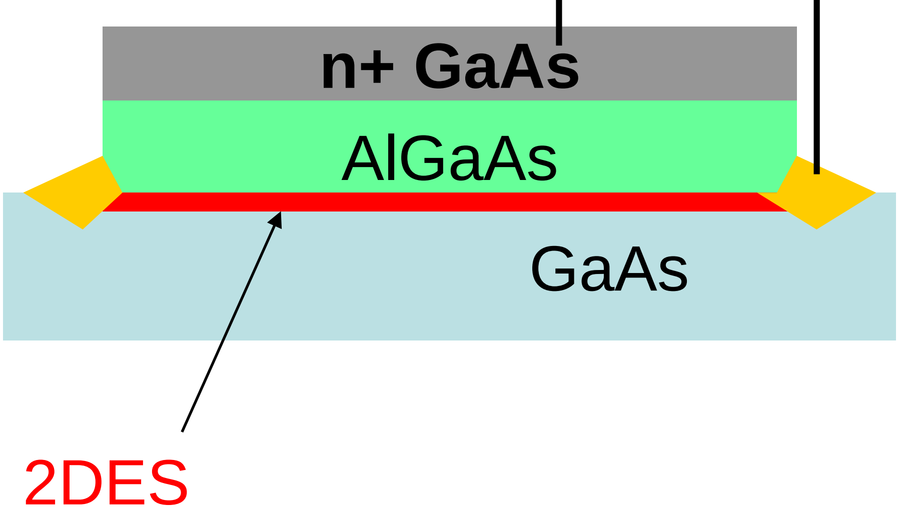


Wang, Avishai, Meir, and Wang, PRB 89, 045314 (2014)

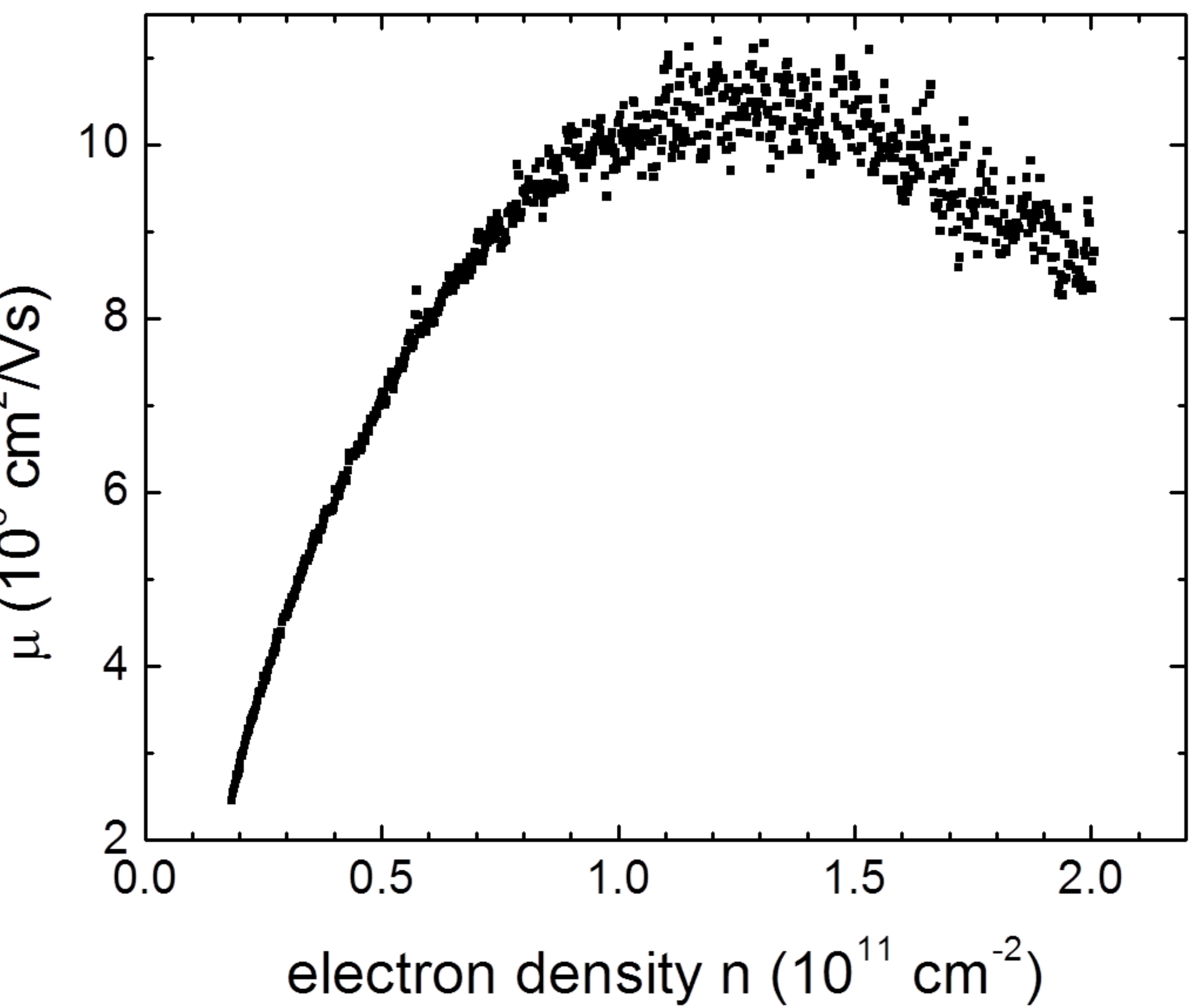
HIGFET
(**H**eterojunction **I**nsulated-**G**ate **F**ield-**E**ffect **T**ransistor)





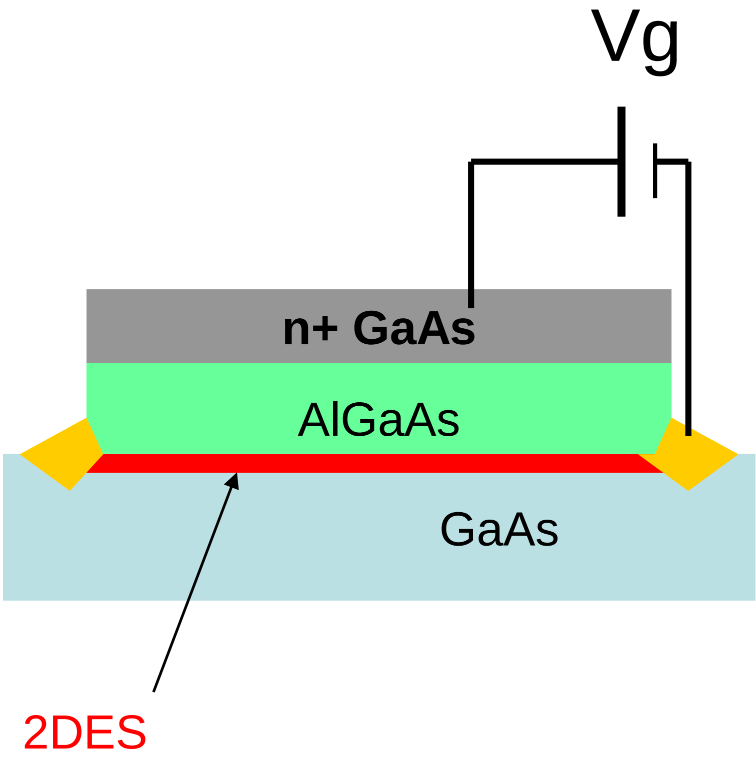


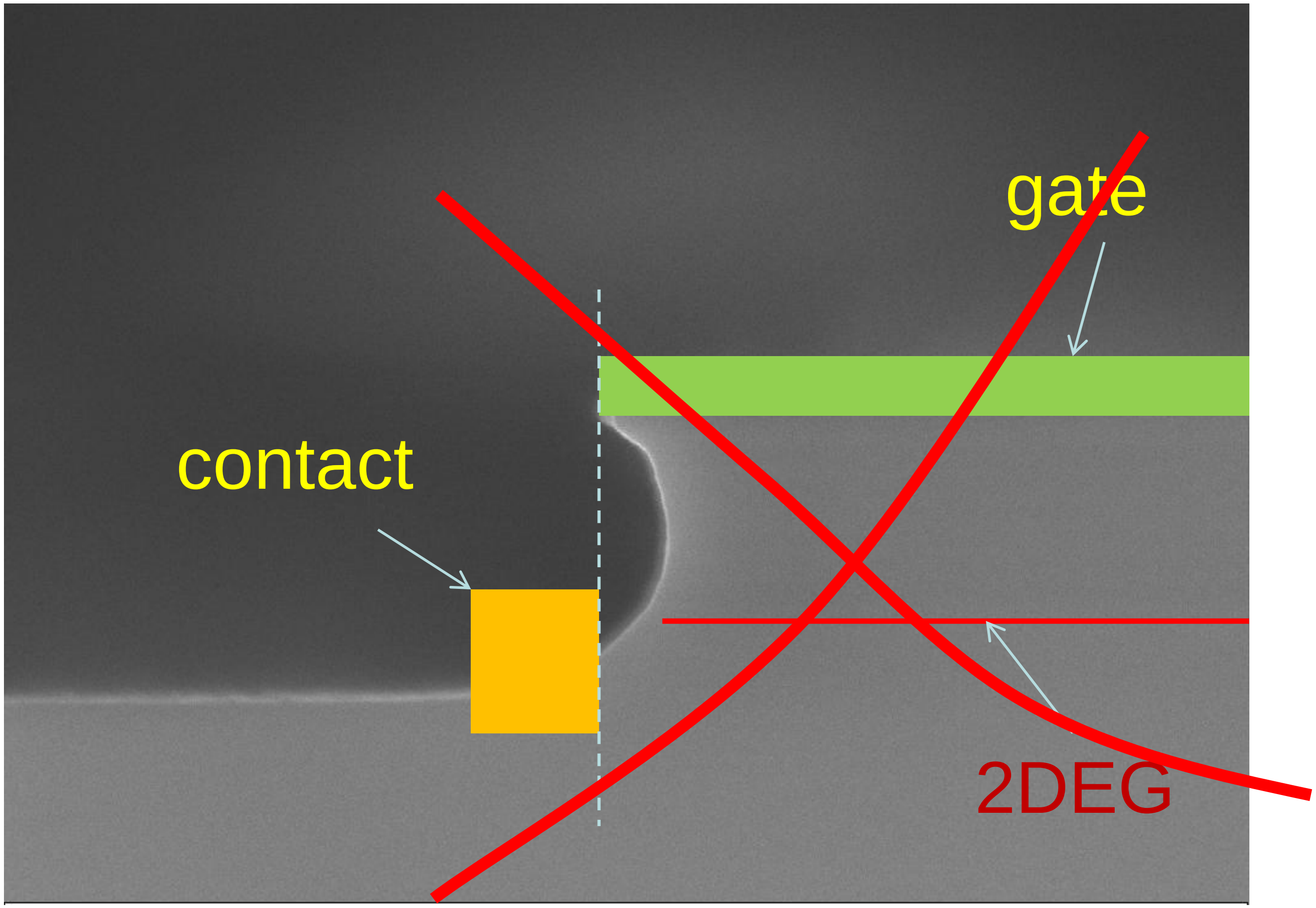
Kane, Pfeiffer, West, and Harnett, APL,1993

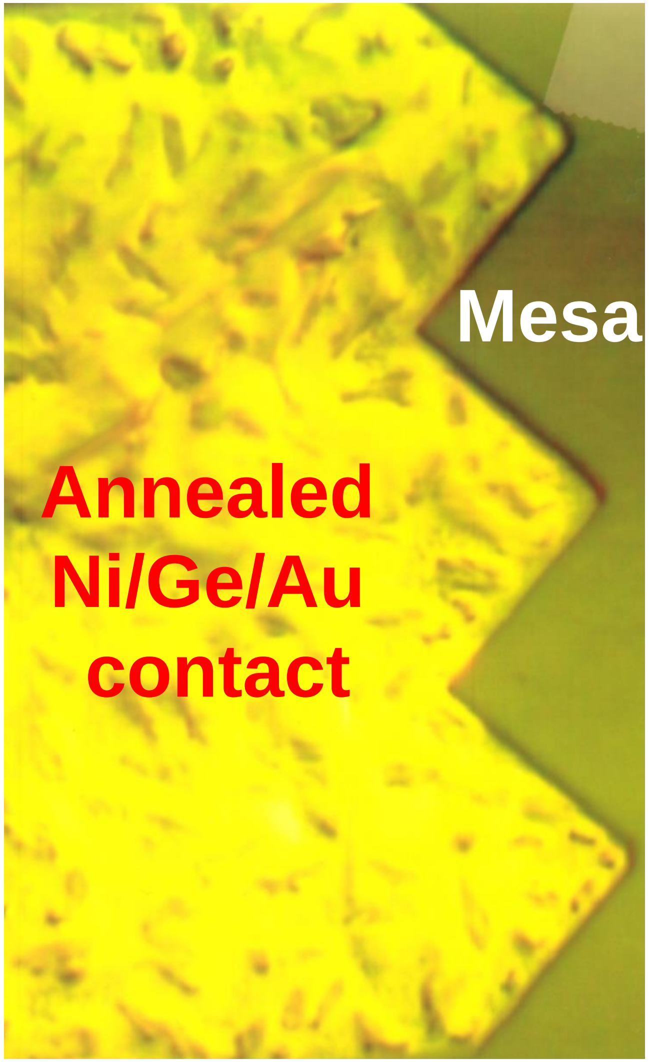


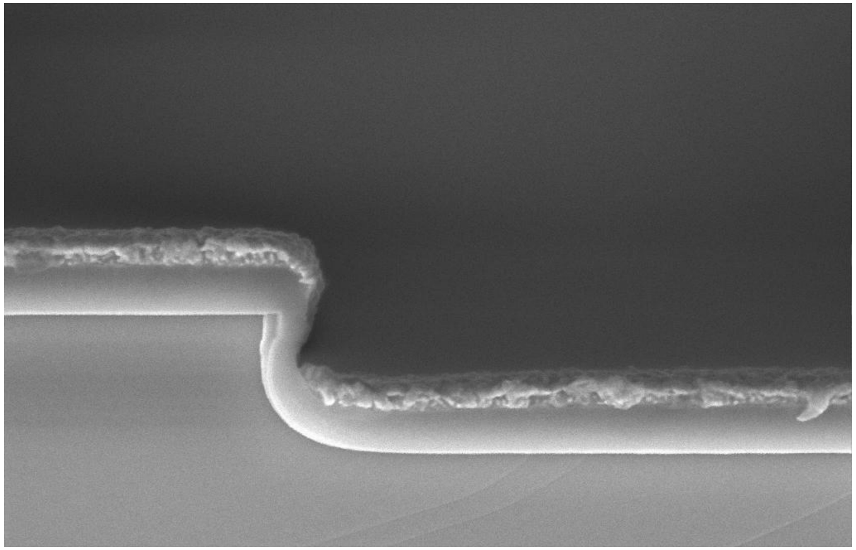
μ (10^6 cm^2/Vs)
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
electron density n (10^11 cm^-2)

Straight sidewall is important




gate
contact
2DEG

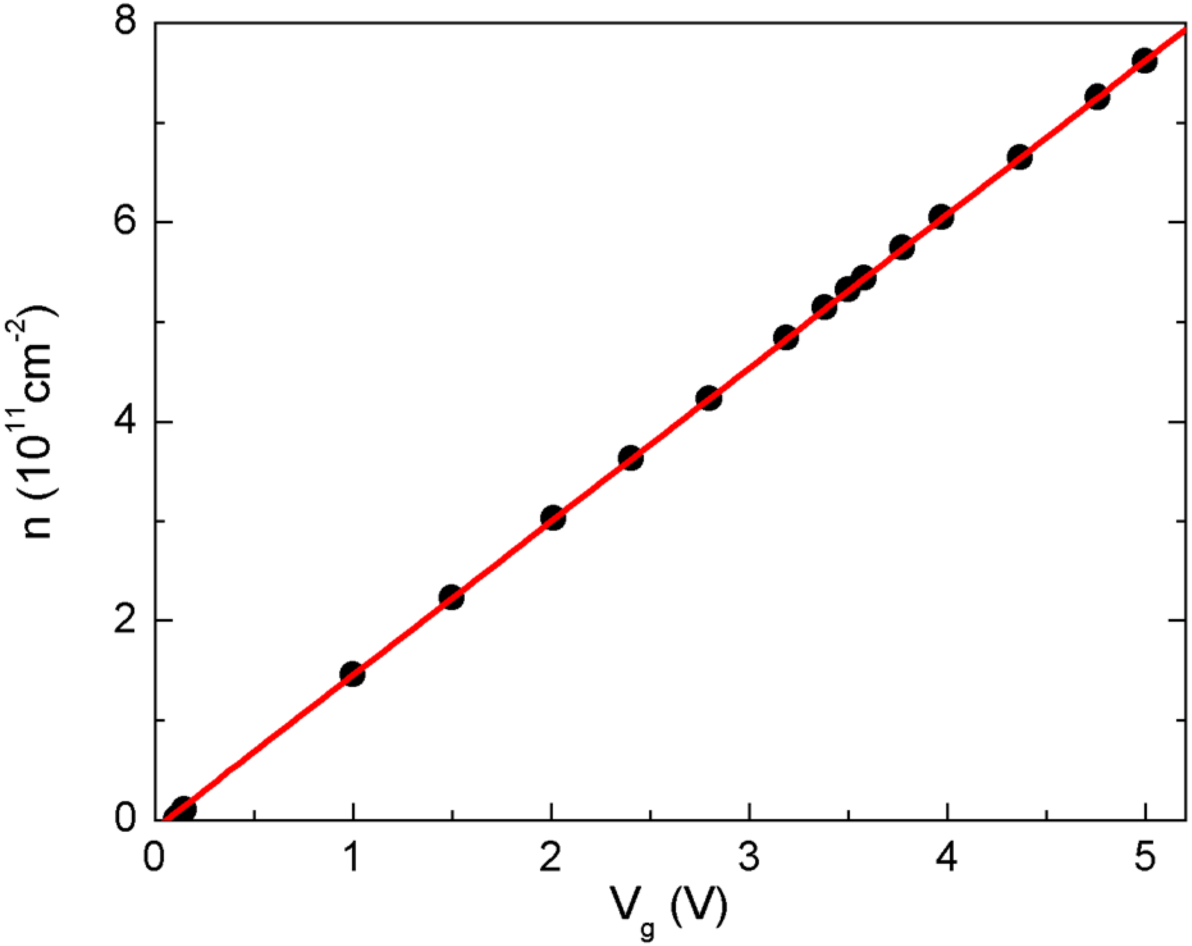




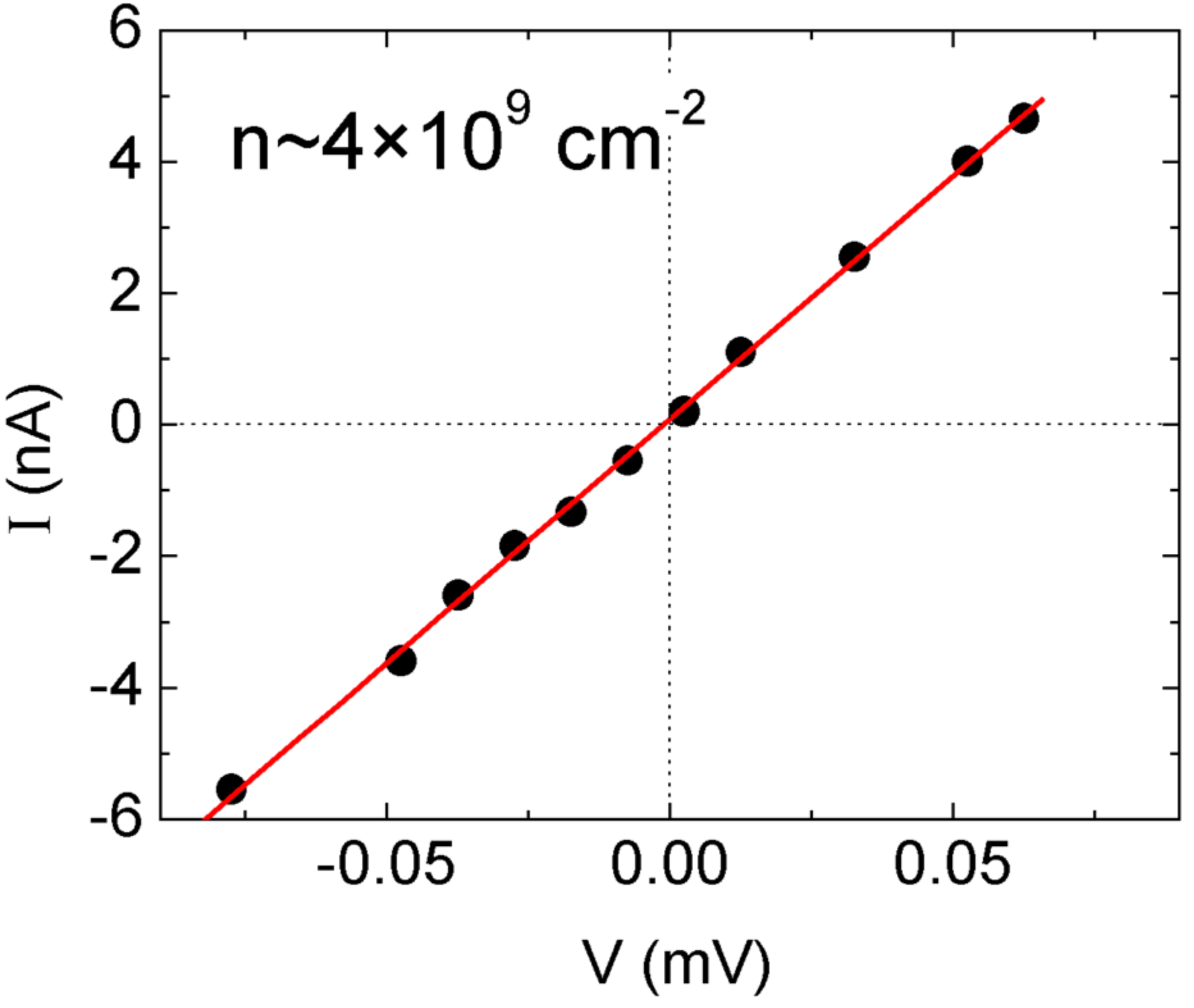
device works!

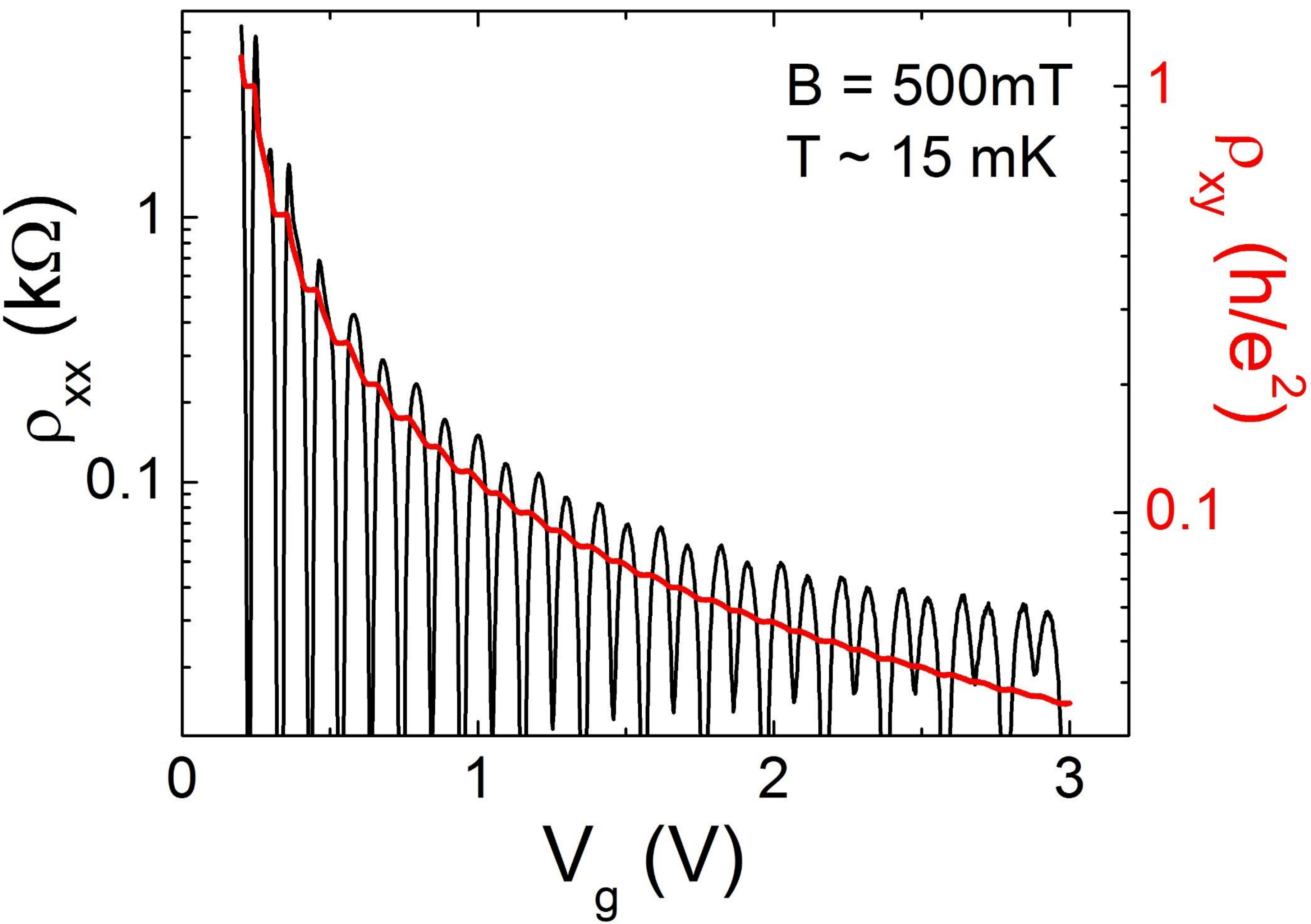
Very large density range

~ 1x10^{9} to ~ 7.5x10^{11} cm^{-2}

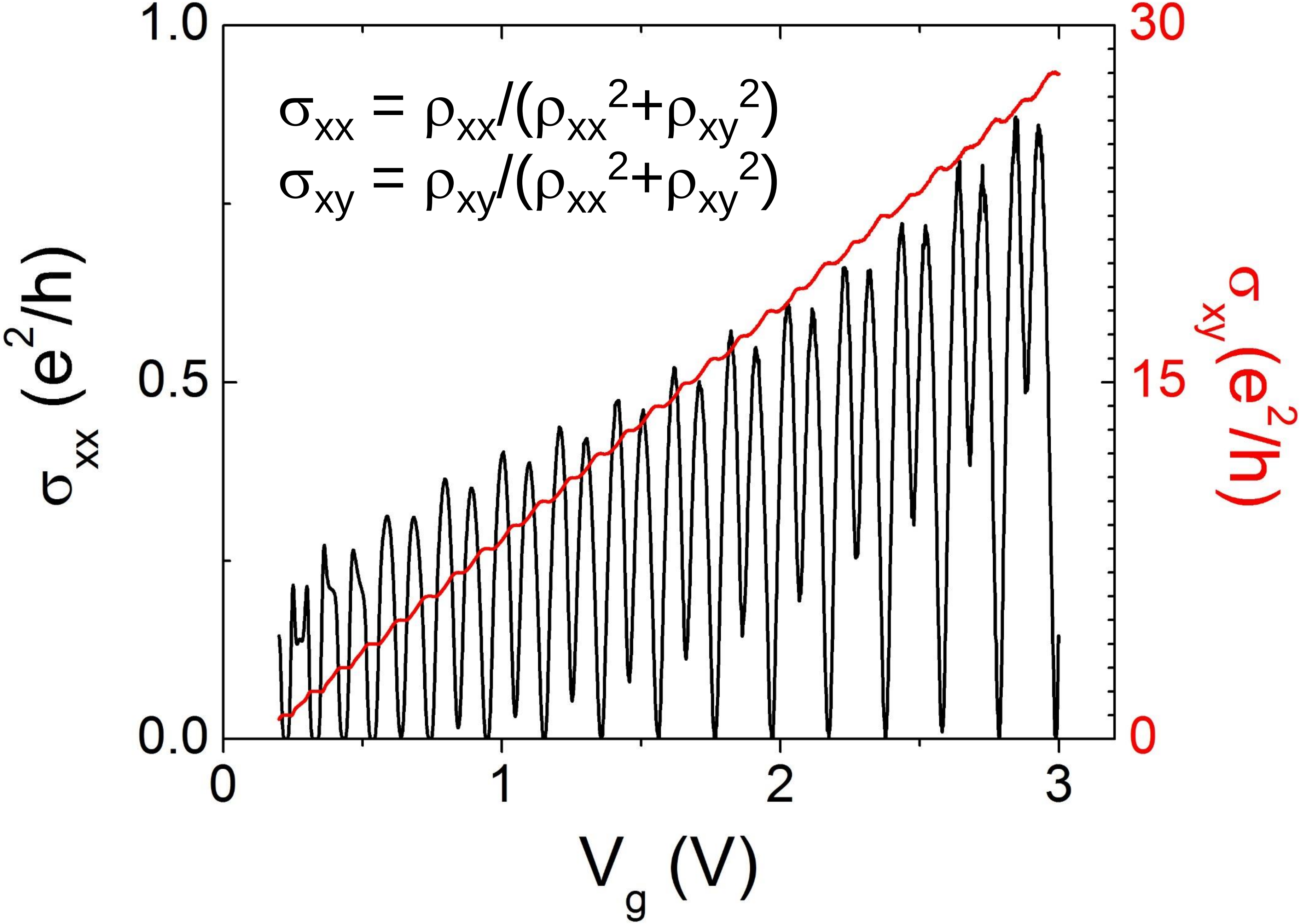


Linear I-V at very low densities



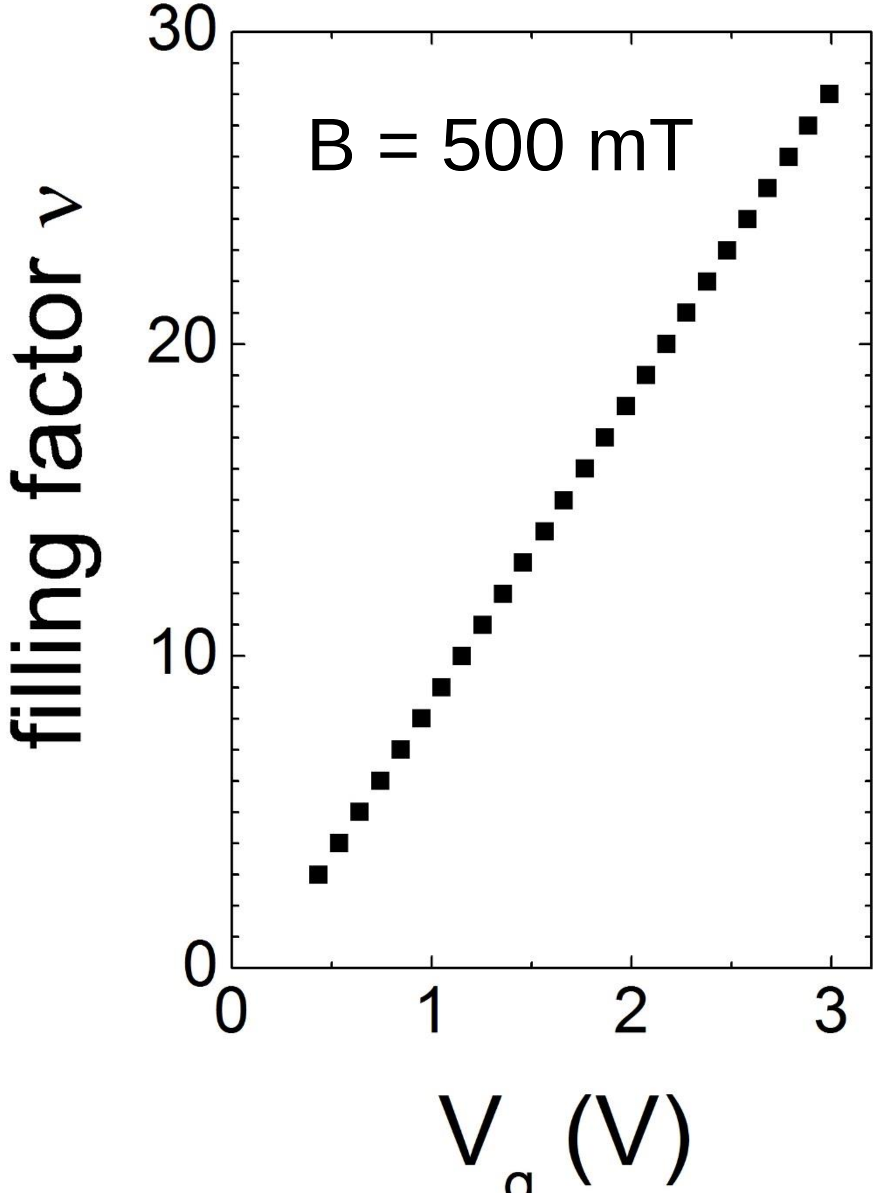


B = 500mT
T ~ 15 mK
ρ_{xx} (kΩ)
ρ_{xy} (h/e^2)
1
0.1
1
0.1
0
1
2
3
V_g (V)

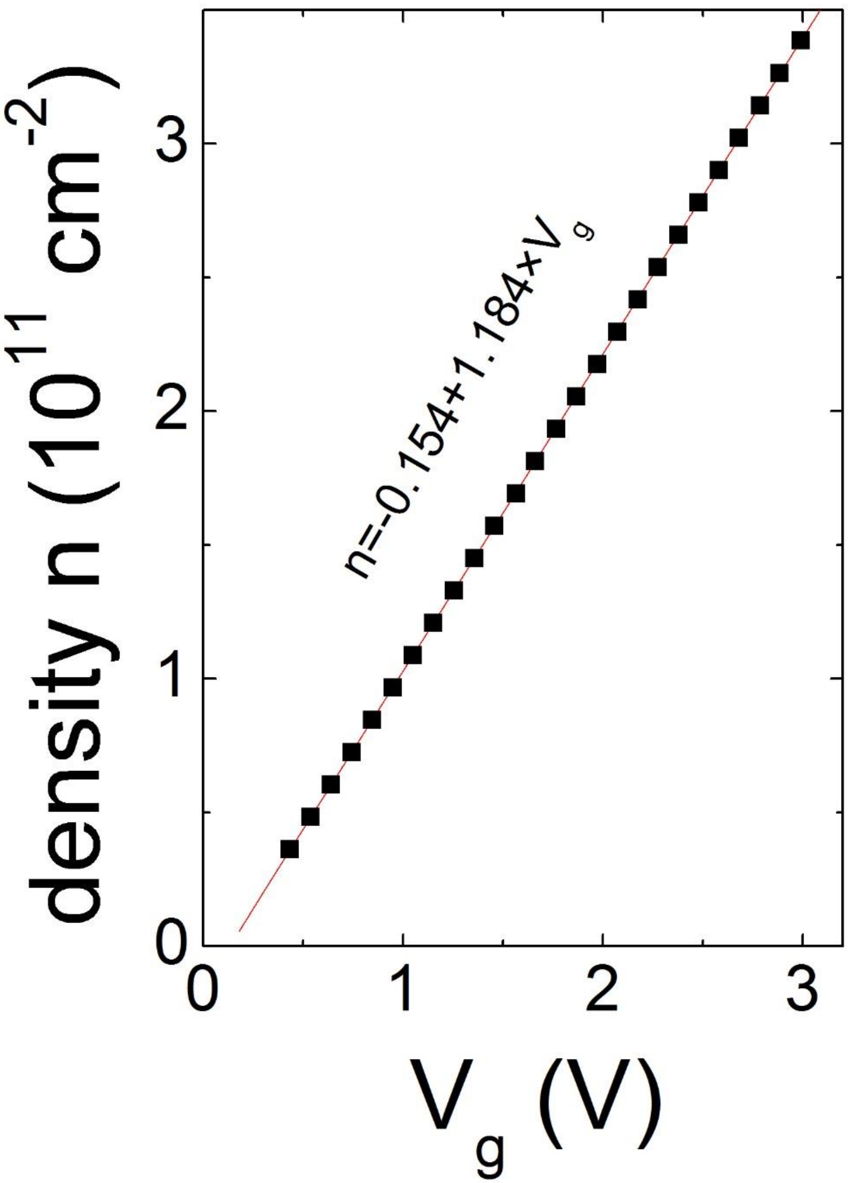


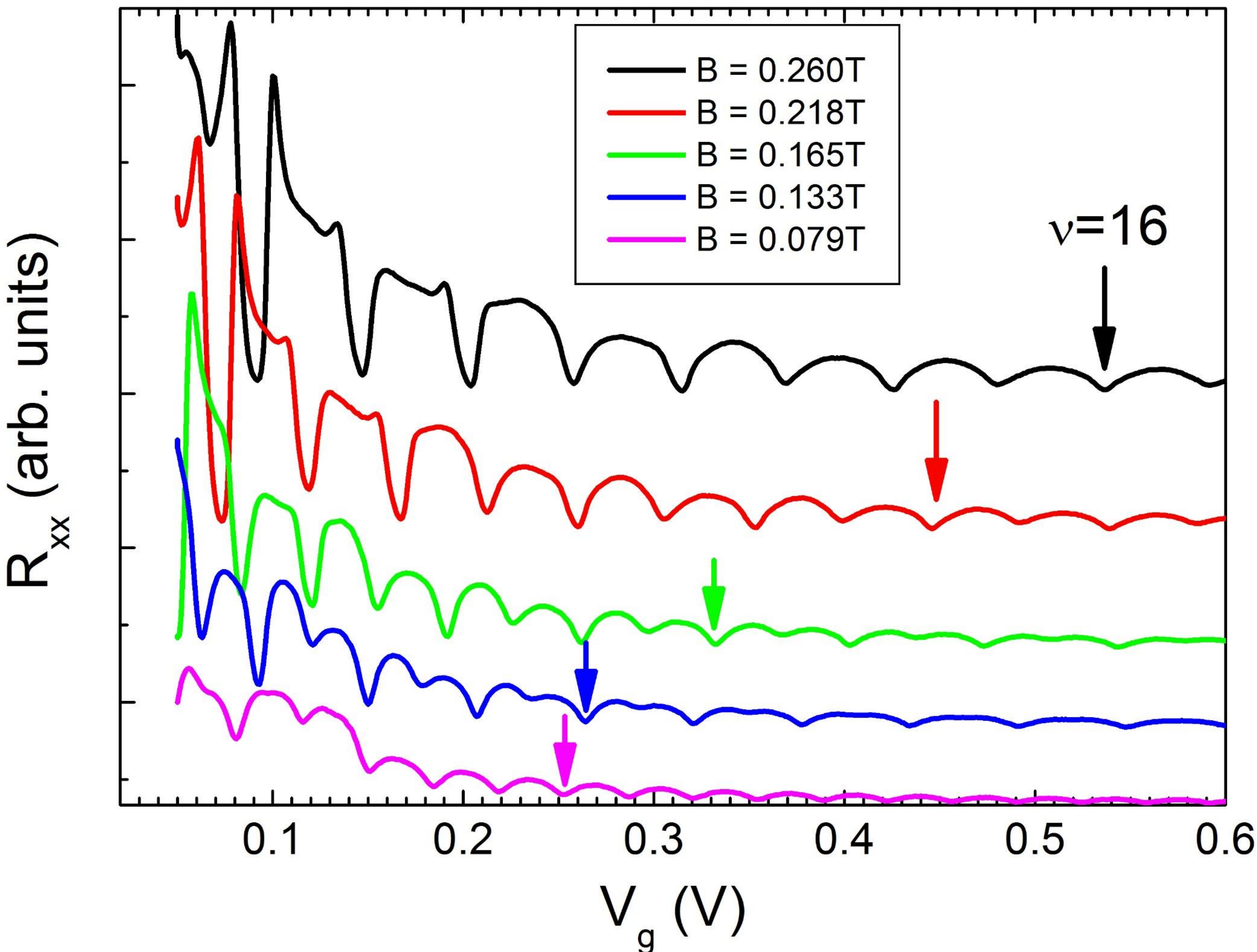
$\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2+\rho_{xy}^2)$
$\sigma_{xy} = \rho_{xy}/(\rho_{xx}^2+\rho_{xy}^2)$
σ_{xx} (e^2/h)
σ_{xy} (e^2/h)
V_g (V)
1.0
0.5
0.0
30
15
0
0
1
2
3

$\nu = nh/eB$

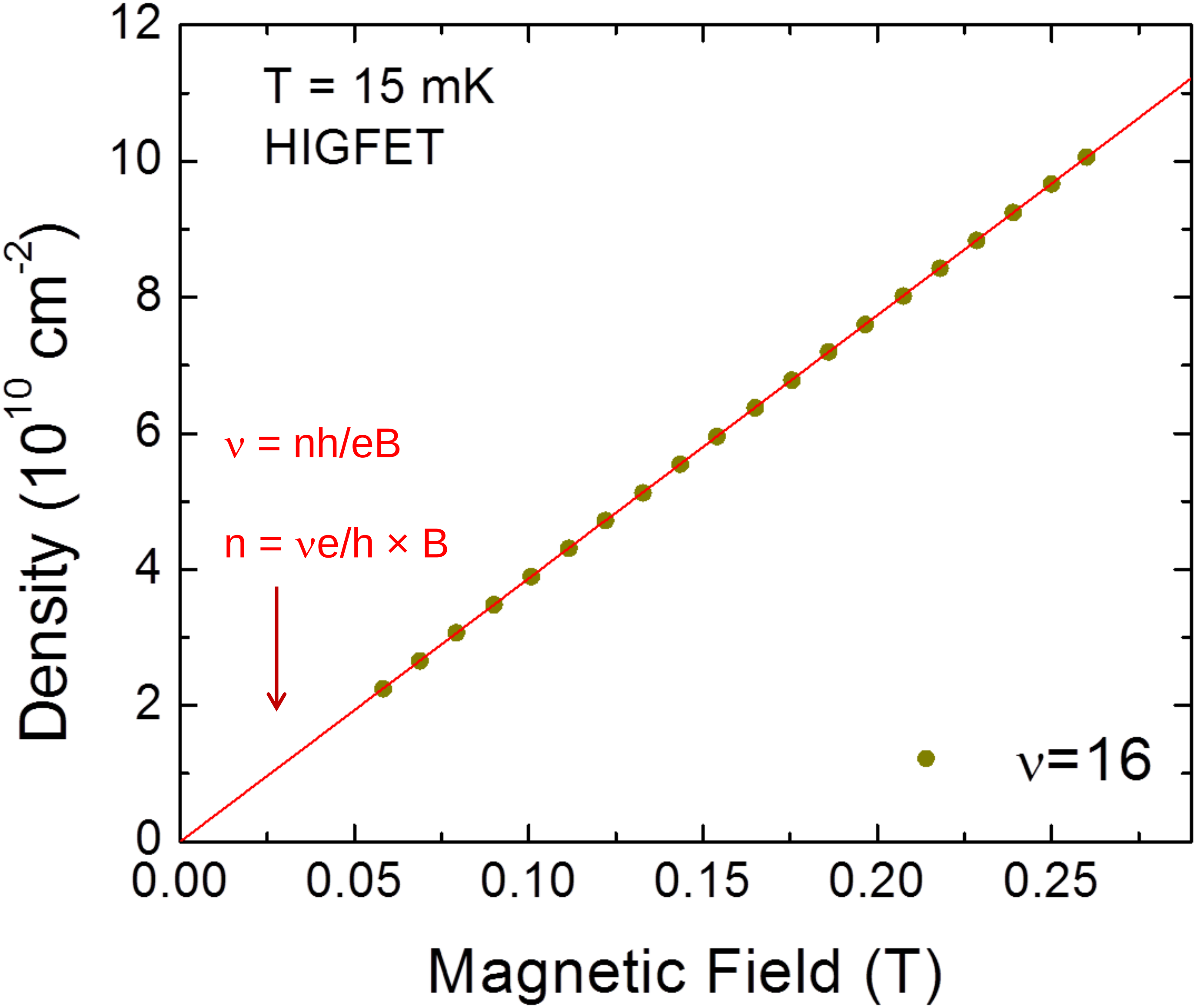


$n = \nu e/h \times B$



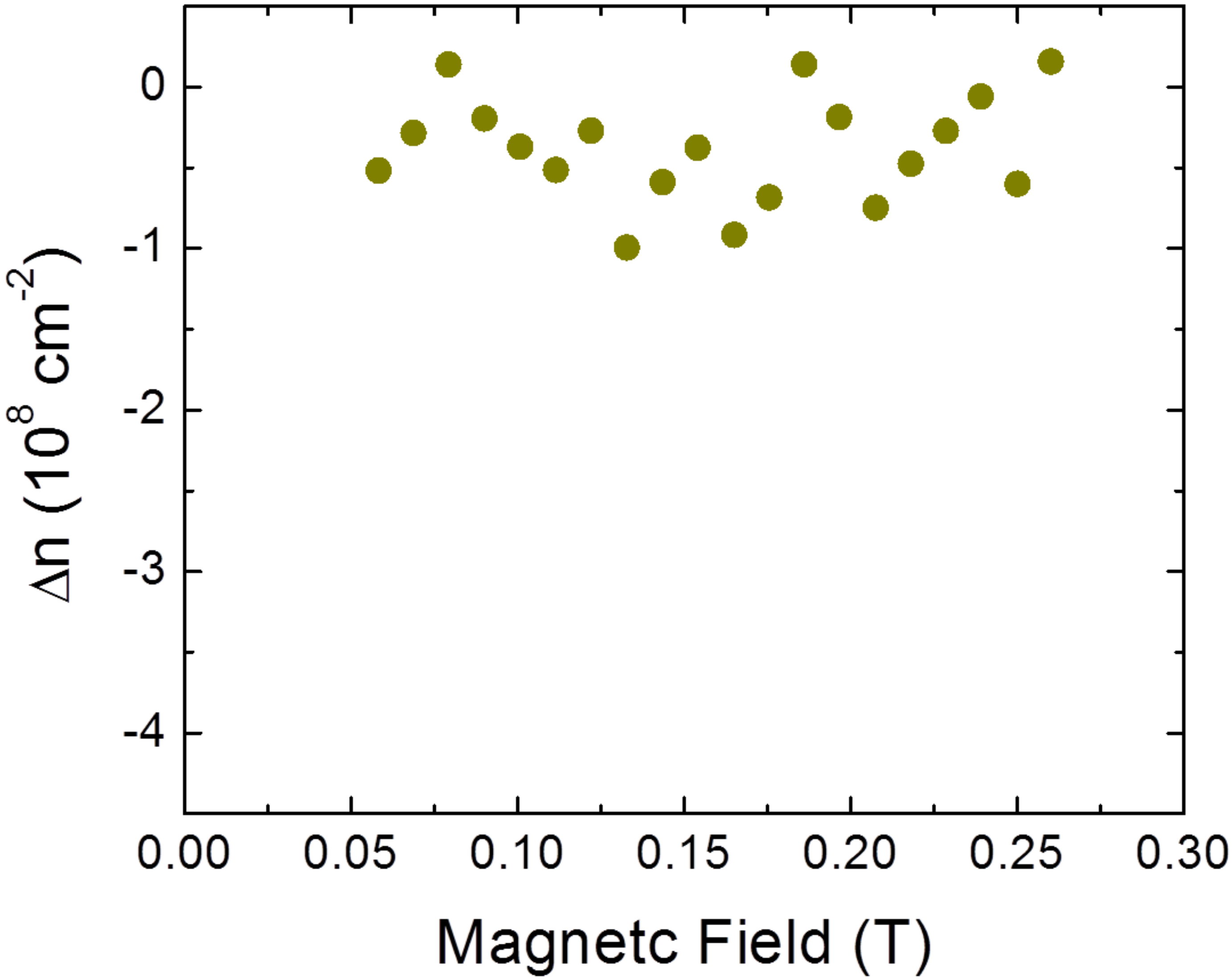


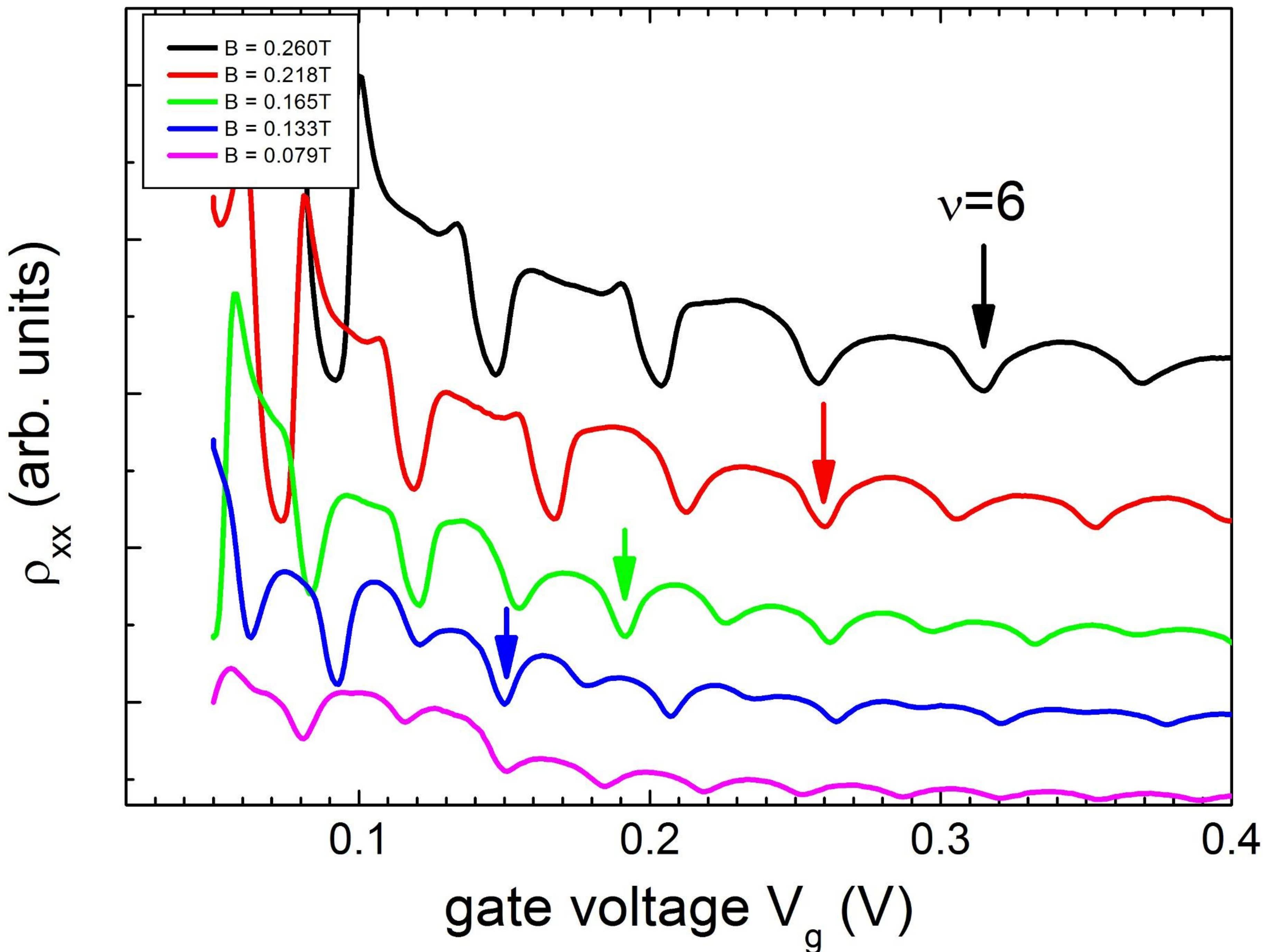
B = 0.260T
B = 0.218T
B = 0.165T
B = 0.133T
B = 0.079T
ν=16
R_{xx} (arb. units)
0.1
0.2
0.3
0.4
0.5
0.6
V_g (V)



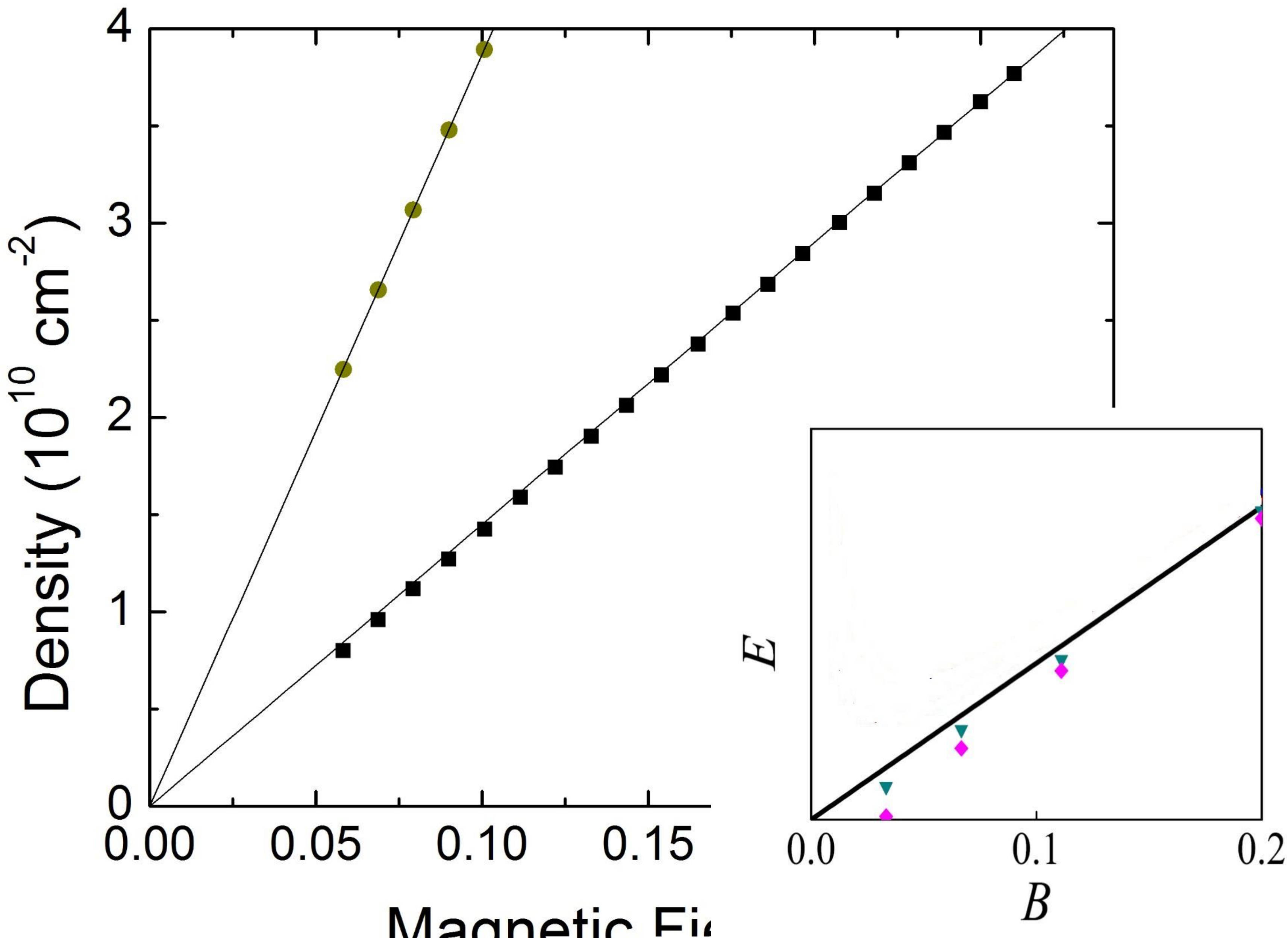
T = 15 mK
HIGFET
ν = nh/eB
n = νe/h × B
ν=16
Density (10^{10} cm^{-2})
Magnetic Field (T)
0
2
4
6
8
10
12
0.00
0.05
0.10
0.15
0.20
0.25

$<\delta n> \approx -4\times10^{7}\ cm^{-2}$

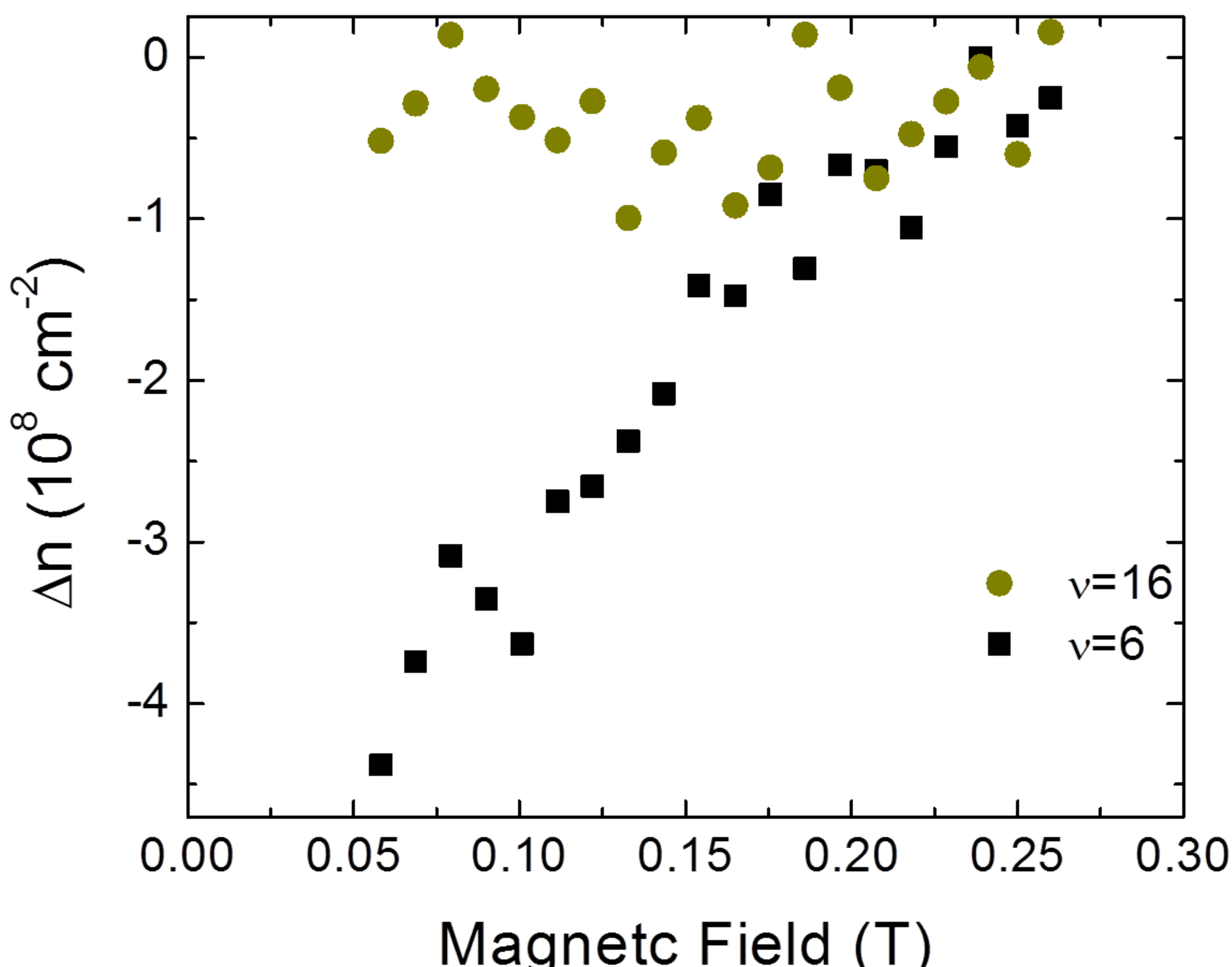


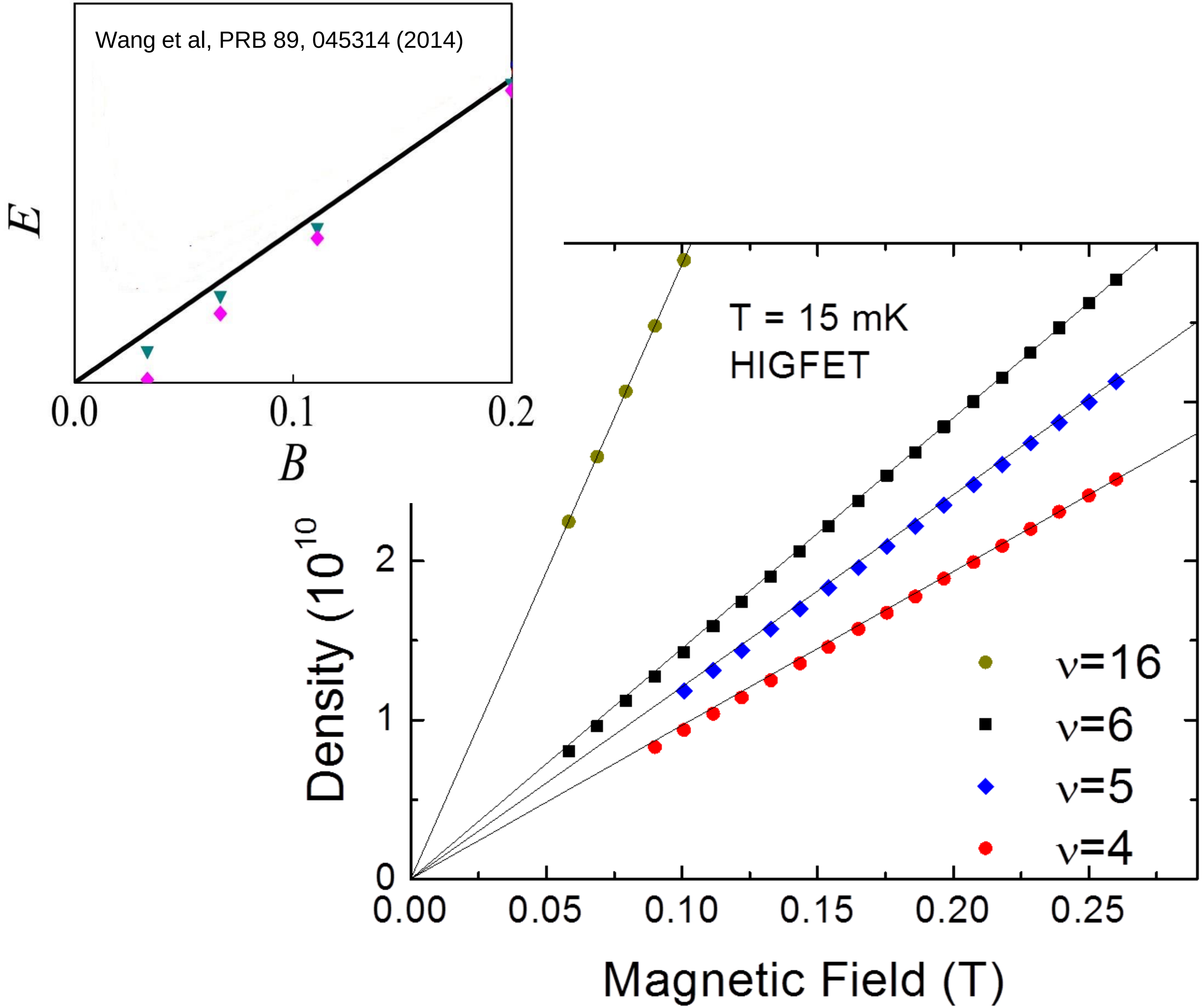


B = 0.260T
B = 0.218T
B = 0.165T
B = 0.133T
B = 0.079T
ν=6
ρxx (arb. units)
0.1
0.2
0.3
0.4
gate voltage Vg (V)



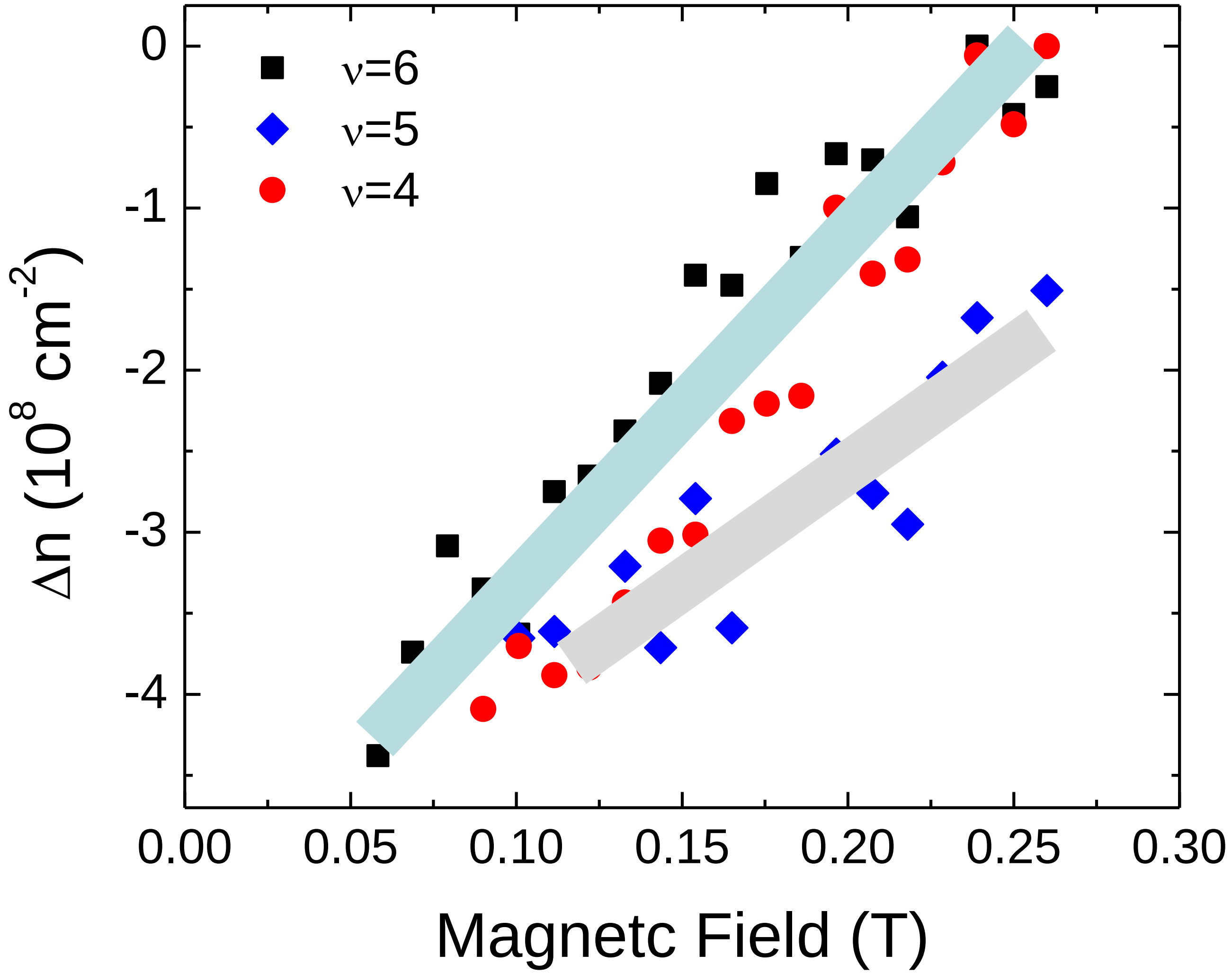
Wang et al, PRB 89, 045314 (2014)


0
-1
-2
-3
-4
Δn (10^8 cm^-2)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Magnetc Field (T)
ν=16
ν=6

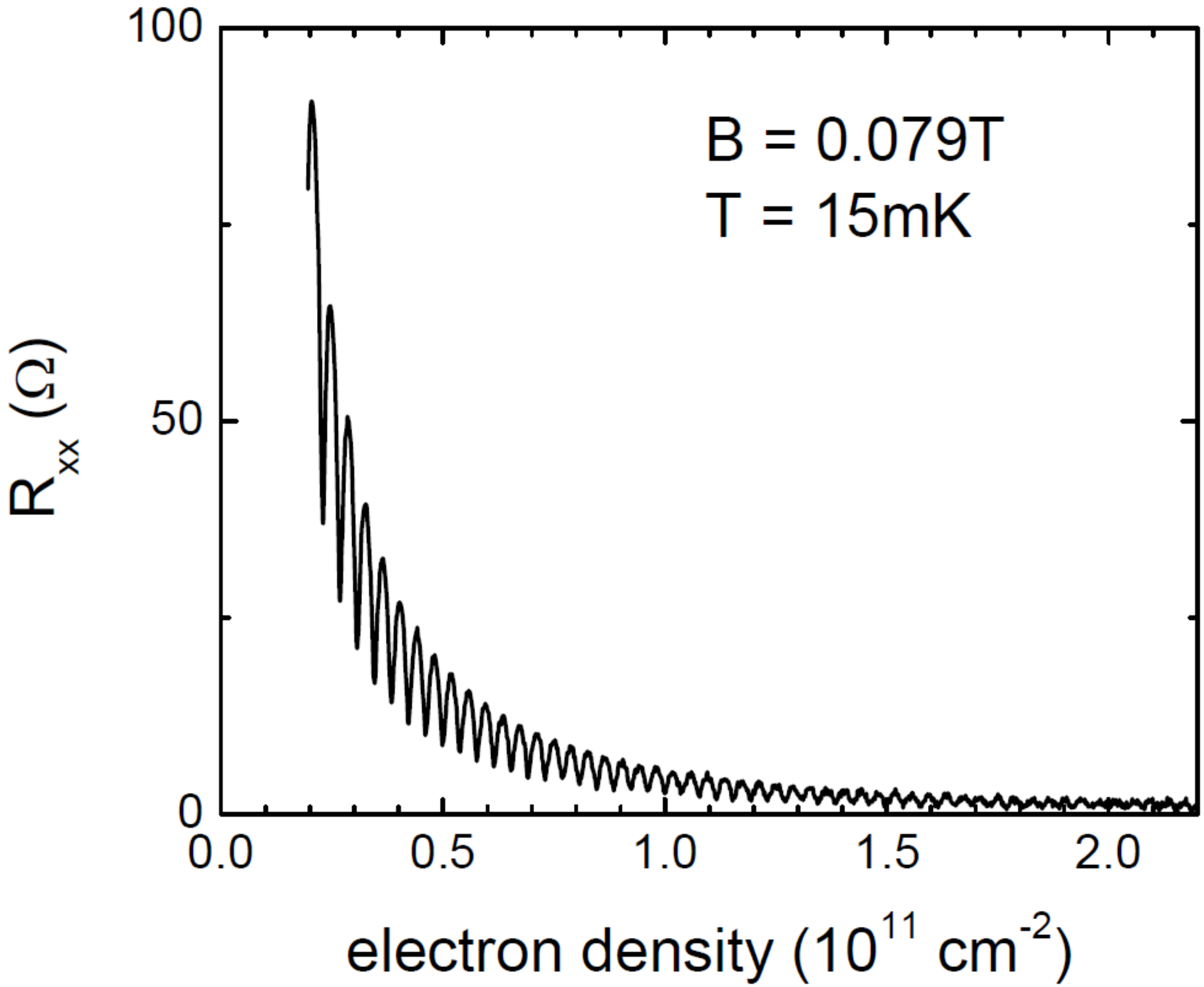


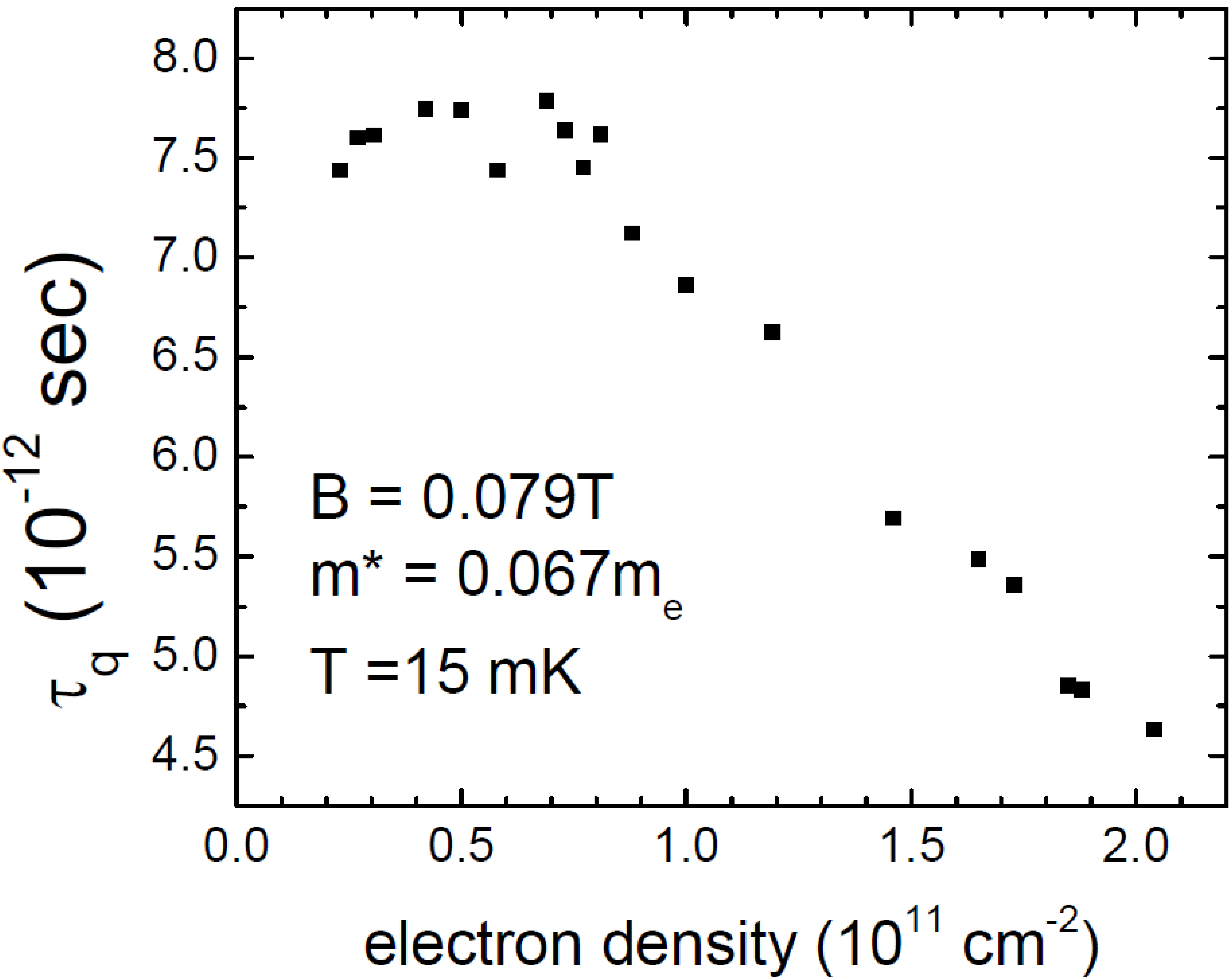
Wang et al, PRB 89, 045314 (2014)
E
0.0
0.1
0.2
B
T = 15 mK
HIGFET
Density (10^{10}
0
1
2
0.00
0.05
0.10
0.15
0.20
0.25
Magnetic Field (T)
ν=16
ν=6
ν=5
ν=4

Observation of anti-floating in vanishing B field



SdH oscillations at B = 0.079T





$$\Delta\rho/\rho = 4x(2\pi^2 k_B T/\hbar\omega_c/\sinh(2\pi^2 k_B T/\hbar\omega_c))x\exp(-\pi/\omega_c\tau_q)$$

$\Delta\rho$ from SdH oscillations, $\rho = 1/(ne\mu)$

part I conclusion

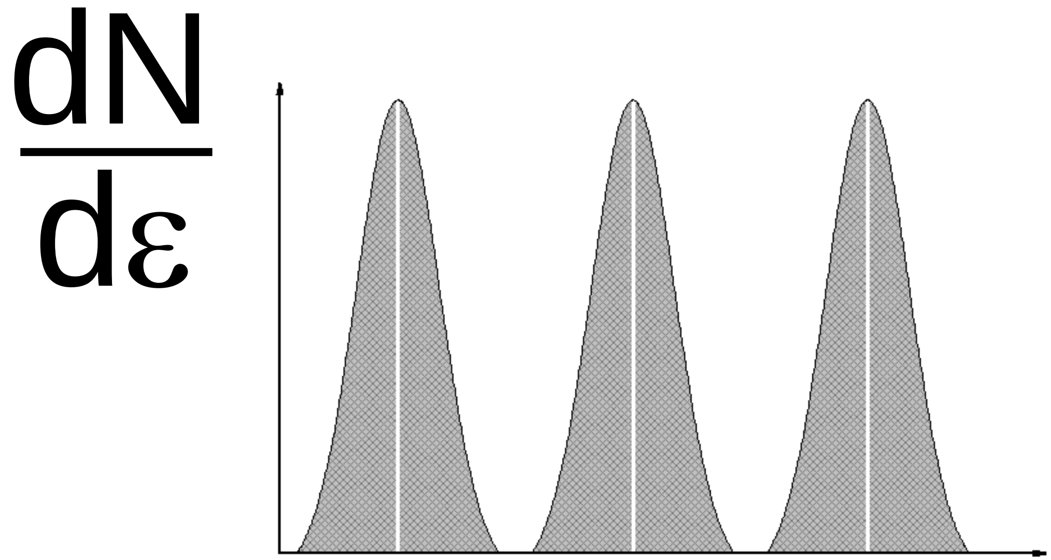
In a high-quality HIGFET, anti-levitation of Landau levels is observed in vanishing magnetic fields.

This observation is in a good agreement with the theoretical prediction (C. Wang et al, PRB 2014).

part II outline

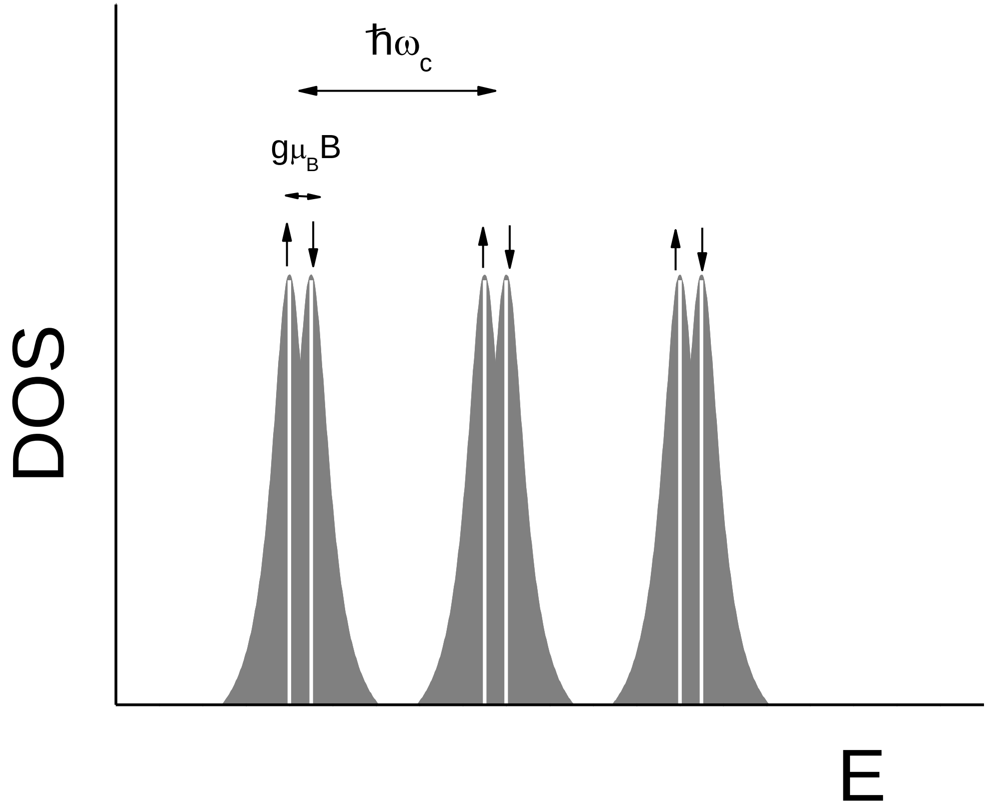
(Collapse of spin splitting in the quantum Hall regime)

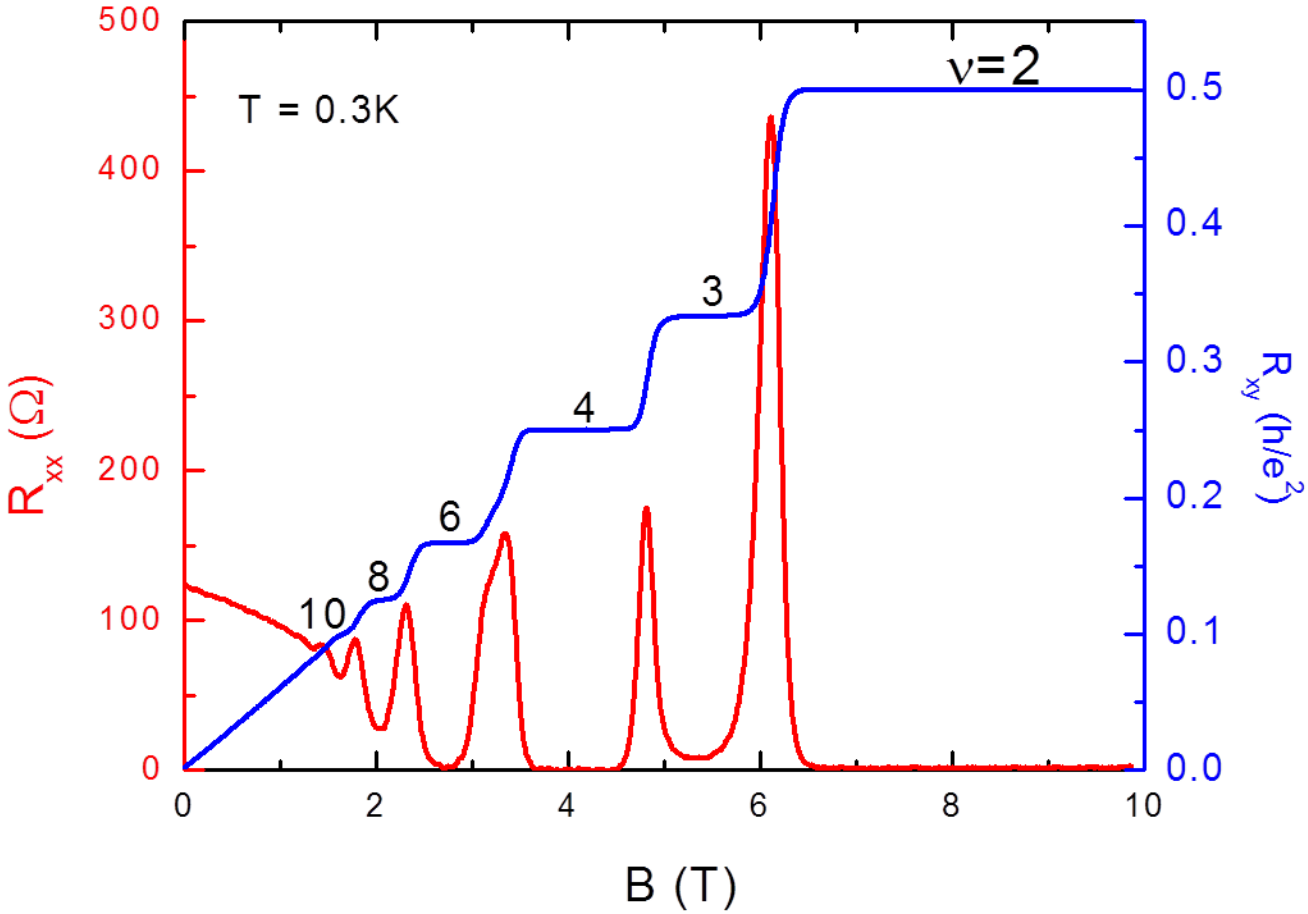
- Background
- Sample
  - HIGFET (**H**eterojunction **I**nsulated-**G**ate **F**ield-**E**ffect **T**ransistor)
- Result
  - Landau level number *N* displays a power-law dependence on 2DEG density n, where the spin splitting collapses.
    - $N = 11.47 \times n^{0.64 \pm 0.01}$ (n is in units of 10^{11} cm^{-2}).
  - This power-law dependence is in good agreement with the theoretical prediction in the low-density regime.



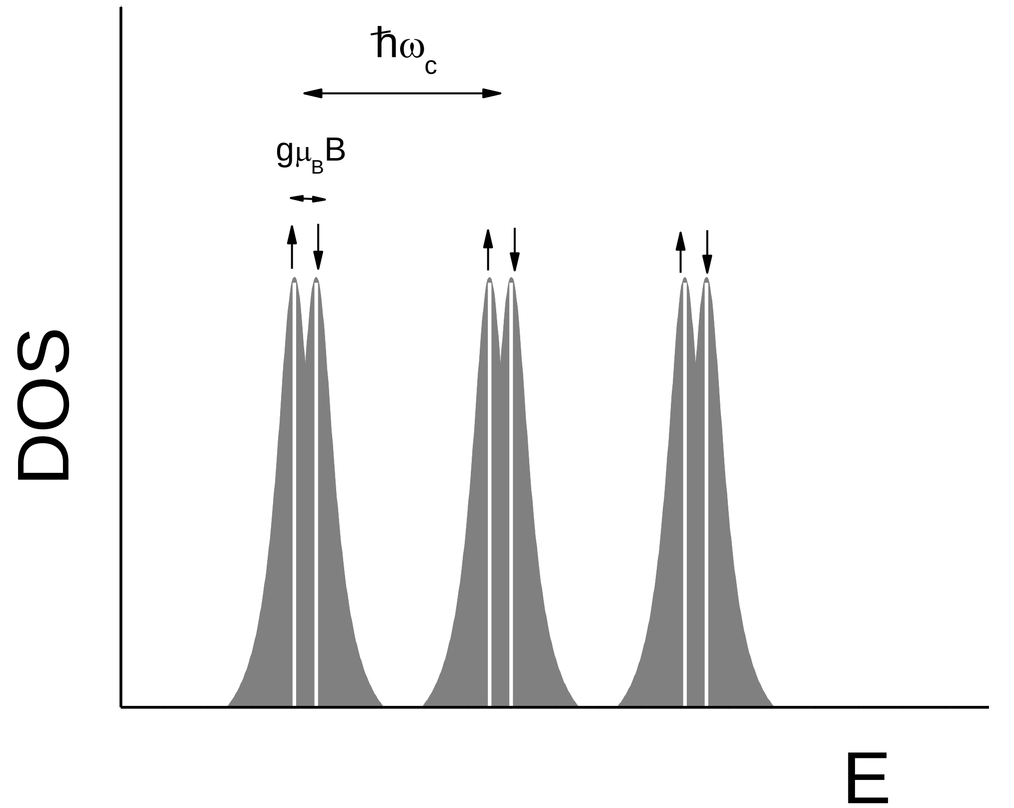
$B \neq 0$

Spin degeneracy lifted





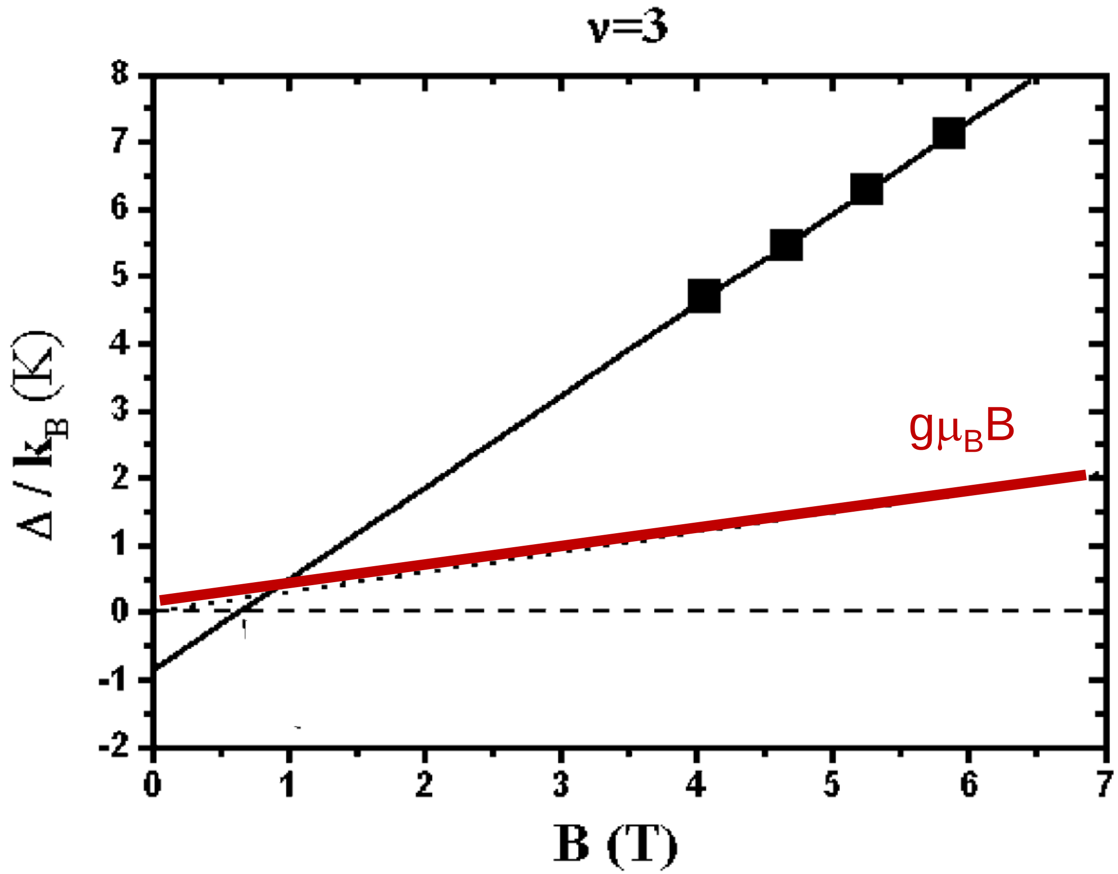
T = 0.3K
ν=2
3
4
6
8
10
R_{xx} (Ω)
R_{xy} (h/e^2)
B (T)
0
100
200
300
400
500
0.0
0.1
0.2
0.3
0.4
0.5
0
2
4
6
8
10



odd Landau level filling states – $\Delta \sim g\mu_B B$

$g = 0.44$, $\mu_B = 0.67$K/Tesla, $B = 5$Tesla, $\Delta \sim 1.5$K

However, odd Landau level filling states – **$\Delta \gg g\mu_B B$**



Huang et al, Physica E 12 (2002) 424 – 427

g factor enhancement

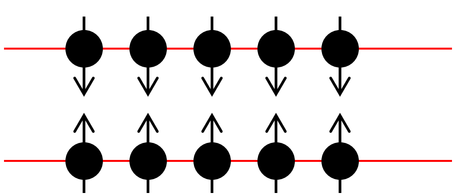
PHYSICAL REVIEW VOLUME 178, NUMBER 3 15 FEBRUARY 1969

g Factor of the Two-Dimensional Interacting Electron Gas

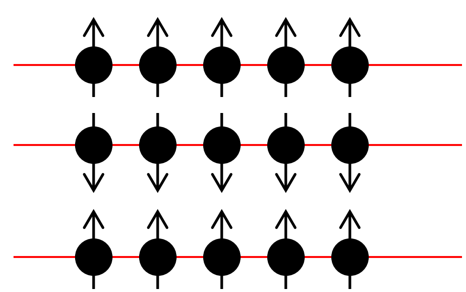
J. F. JANAK
IBM Watson Research Center, Yorktown Heights, New York 10598
(Received 27 September 1968)

$$g^*\mu_B \cdot B = g\mu_B \cdot B + E_{ex}\sum_{N'}(n_{N'\uparrow} - n_{N'\downarrow}).$$

E_{ex} is the exchange parameter
$n\uparrow$, $n\downarrow$ are the occupation factors of the spin levels.



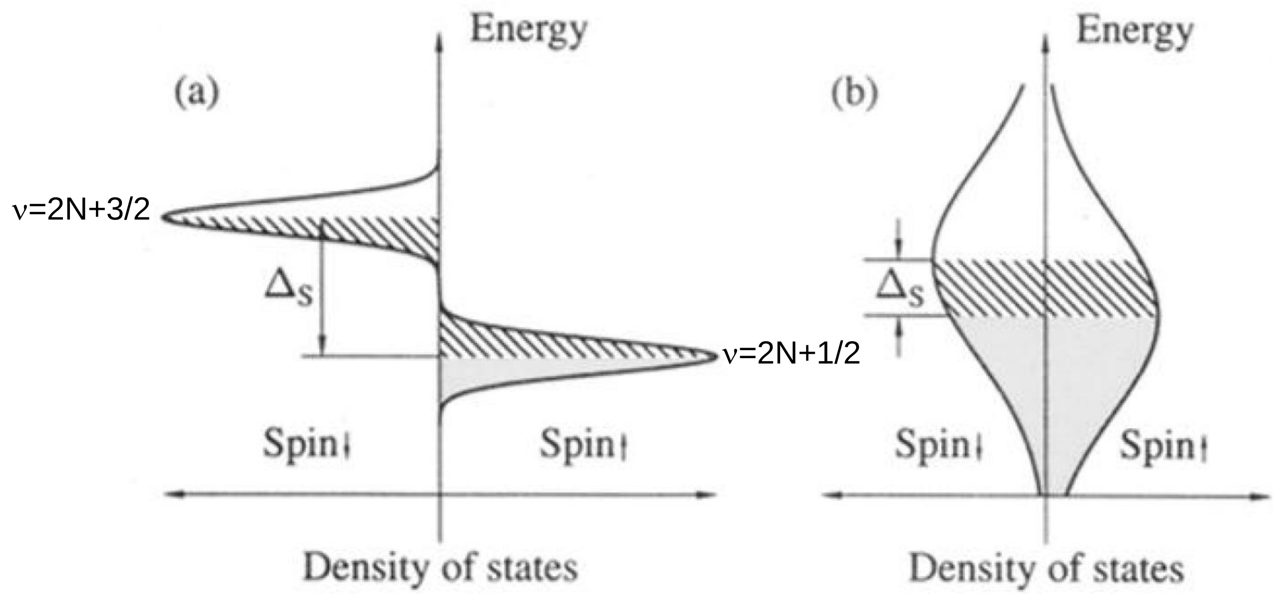
$\nu = 2$
$n\uparrow = n\downarrow$



$\nu = 3$
$n\uparrow > n\downarrow$

disorder-induced destruction of exchange enhancement

Fogler and Shklovskii [PRB **52**, 17366 (1995)]



width of Landau level << Δ_s

$\Delta\nu = 1$

width of Landau level ~ Δ_s

$\Delta\nu \rightarrow 0$

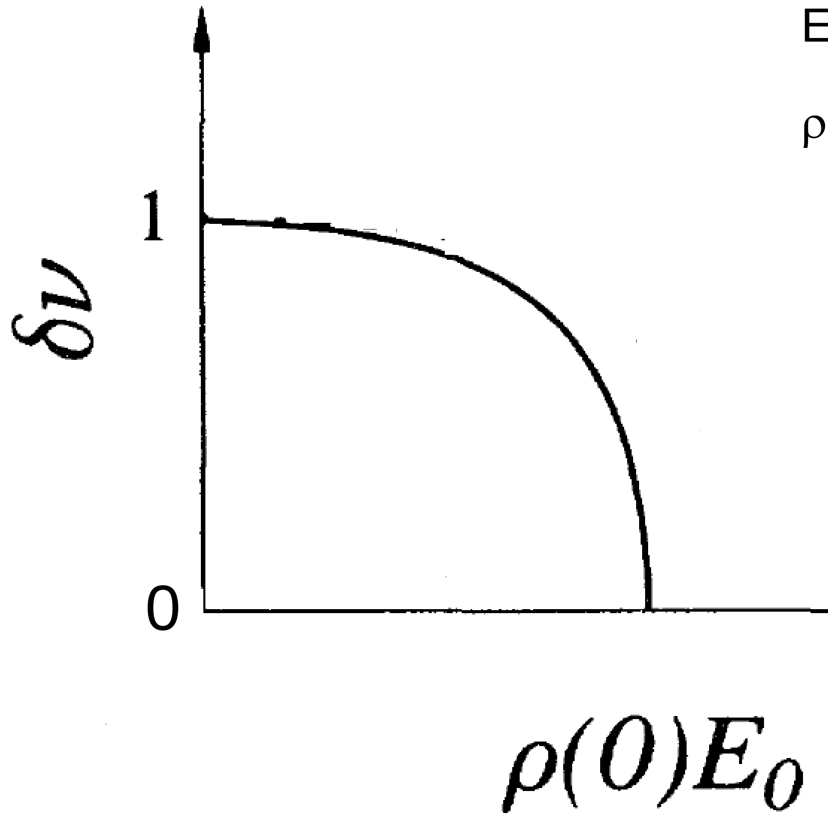
$\Delta\nu$ = the Landau level filling between spin-up and spin-down bands

a second-order phase transition

$$\rho(0) = \hbar^{-1}\sqrt{(2/\pi)(\tau/\omega_c)}$$

$E_0 \propto \hbar\omega_c$

$\rho(0)E_0 \propto (\mu B)^{1/2}$



theoretical prediction

Fogler and Shklovskii [PRB **52**, 17366 (1995)]

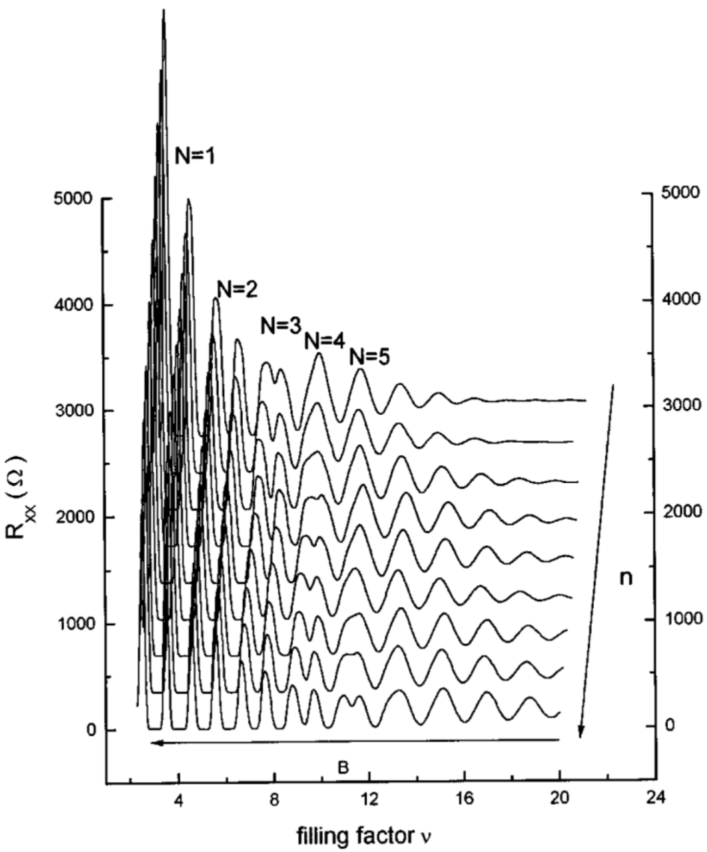
In high mobility GaAs/AlGaAs heterostructures:

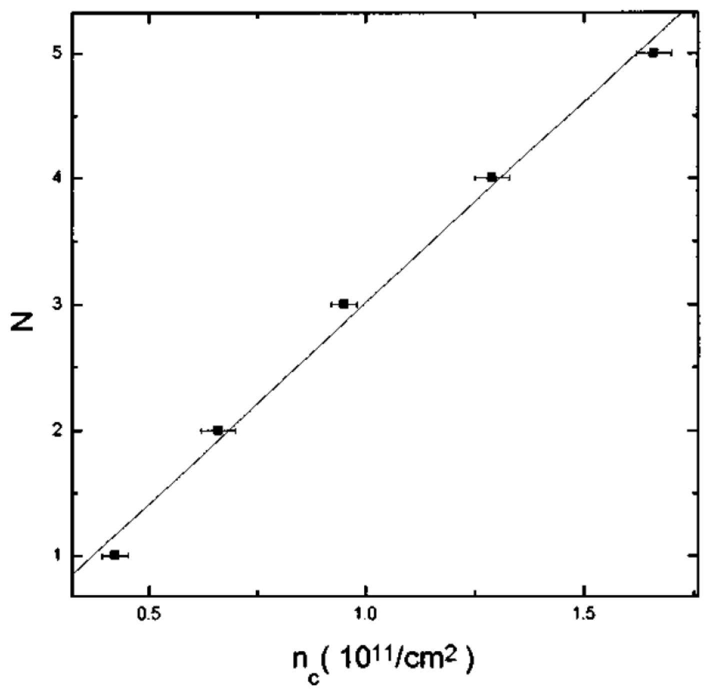
$$N_c = \begin{cases} \sqrt{8\pi}\,\alpha^2 n^{3/2} n_i^{-1} = 0.02d \dfrac{n^{1/2}\ln^2(8\pi n a_B^2)}{n_i a_B^2}, \quad n \gtrsim n_* & \text{(4a)} \\ 0.9d \dfrac{n^{5/6}}{n_i^{1/3}}, \quad n_i \lesssim n \lesssim n_* & \text{(4b)} \\ 0.9d \dfrac{n^{2/3}}{n_i^{1/6}}, \quad n \lesssim n_i, & \text{(4c)} \end{cases}$$

low density regime: $N_c \propto n^{2/3}$

previous experimental work

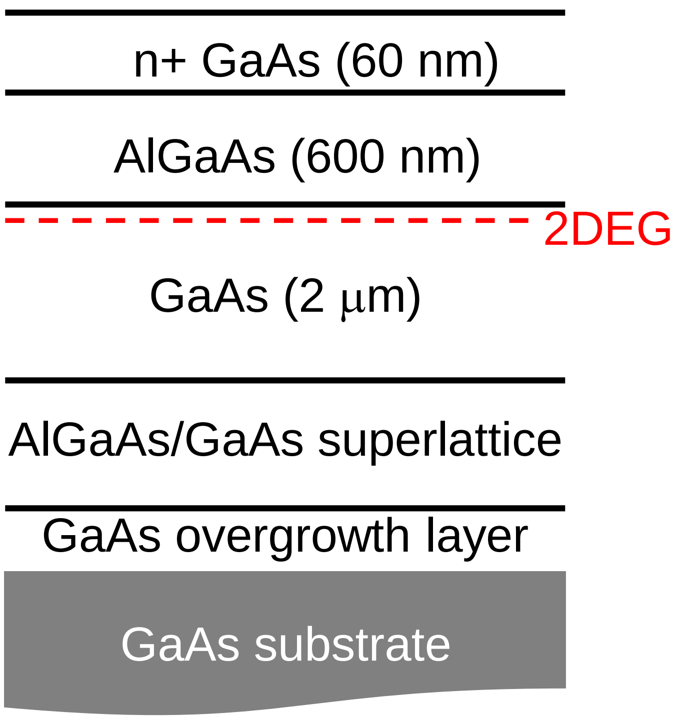
Wong, Jiang, Palm, and Schaff, PRB **55**, R7343 (1997).

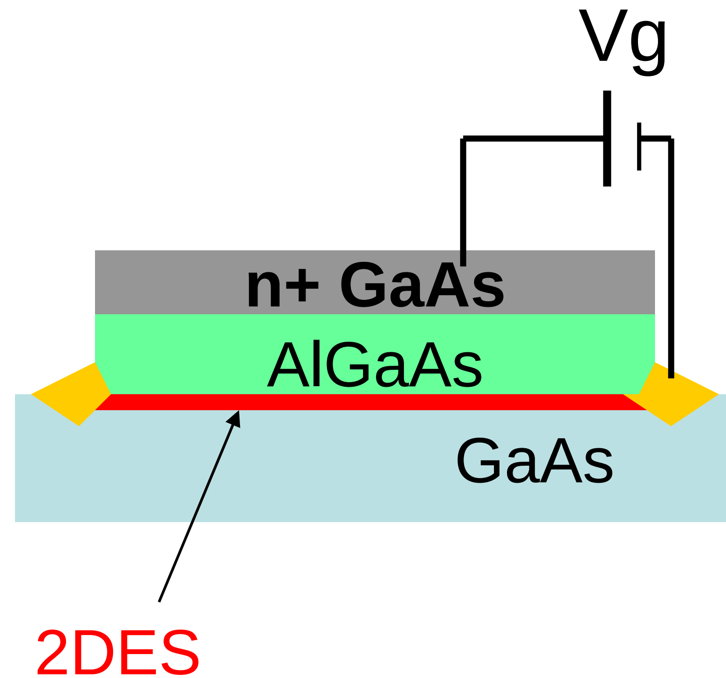




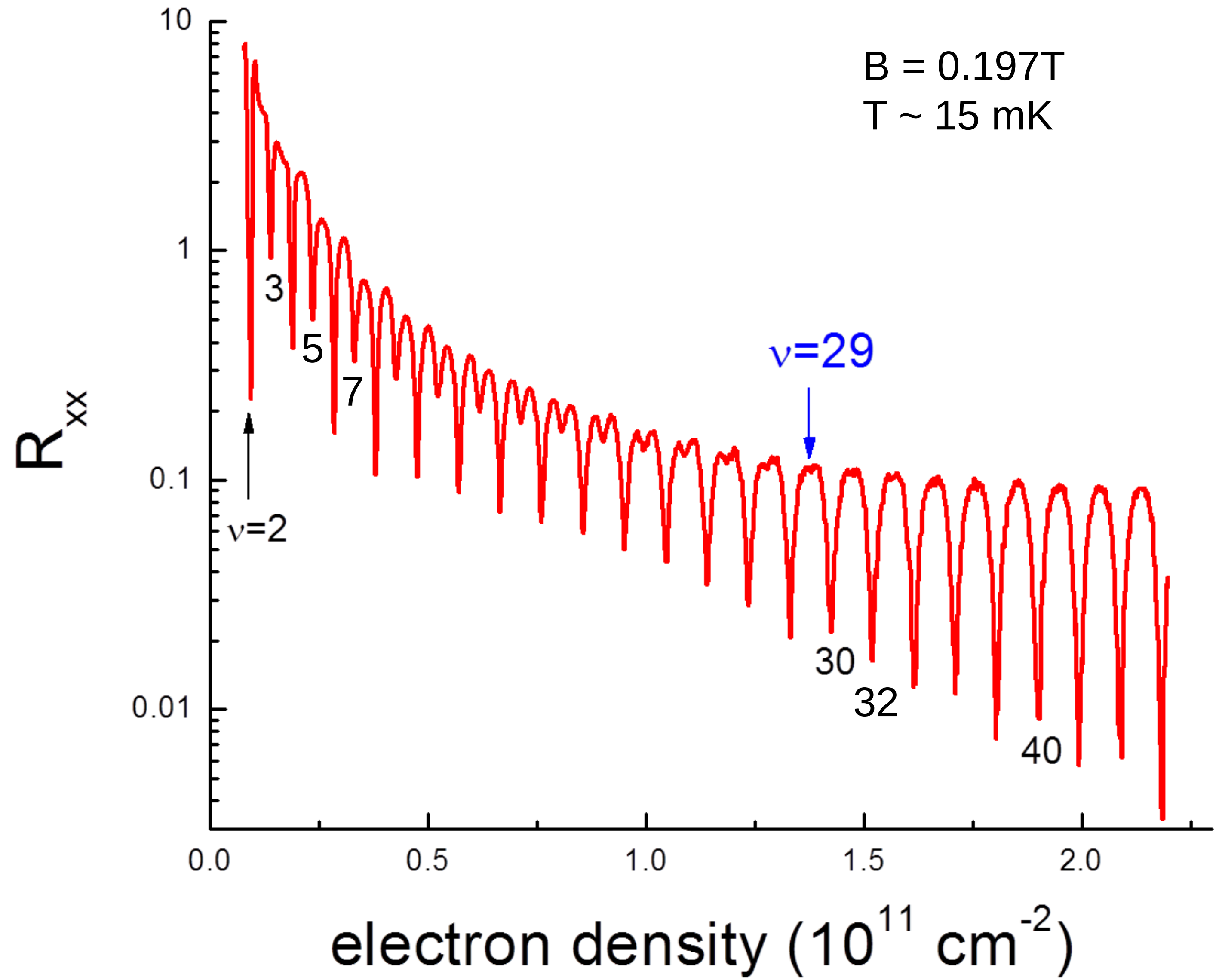
sample peak mobility < 10^6 cm^2/Vs

HIGFET
high mobility down to low densities

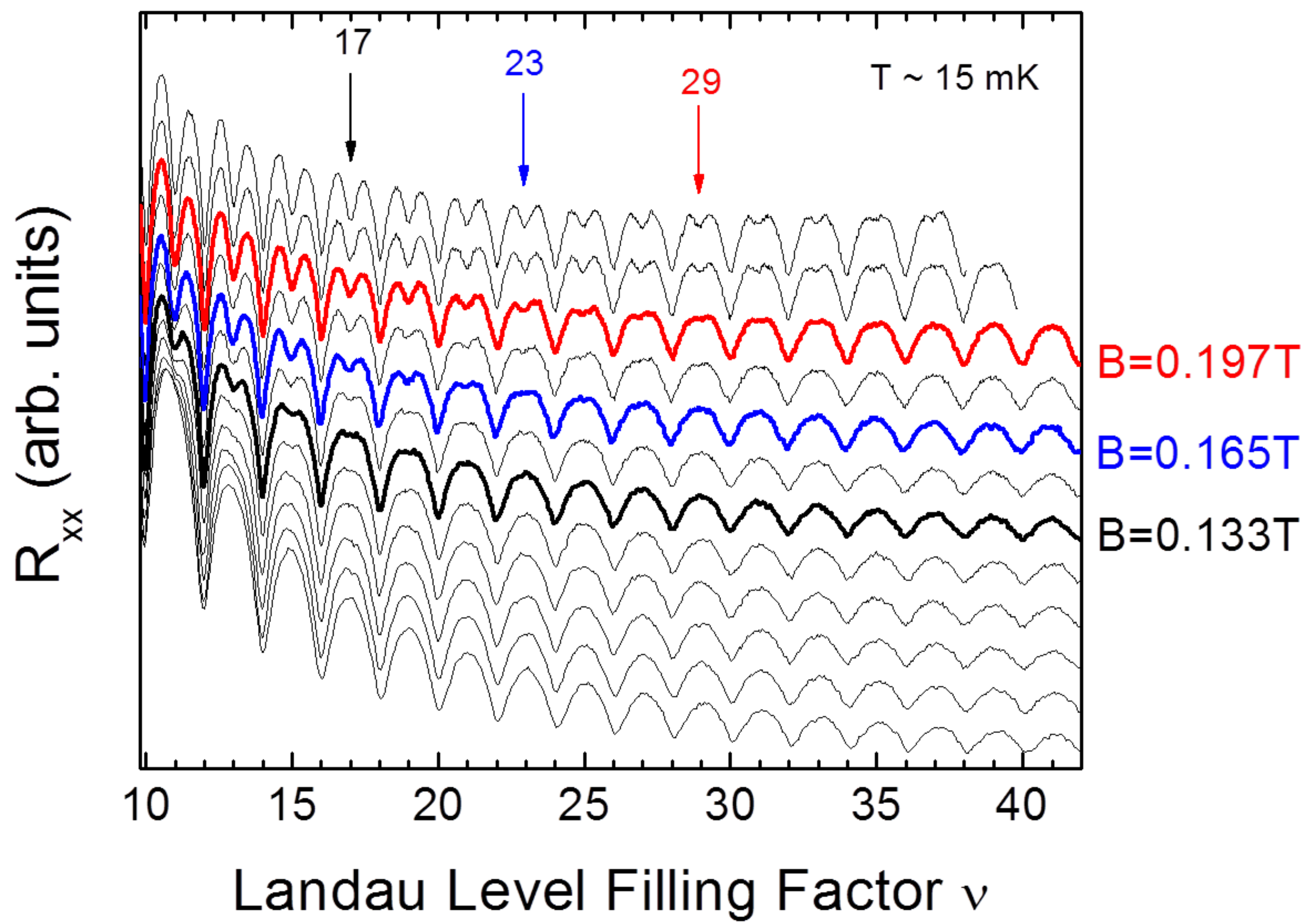




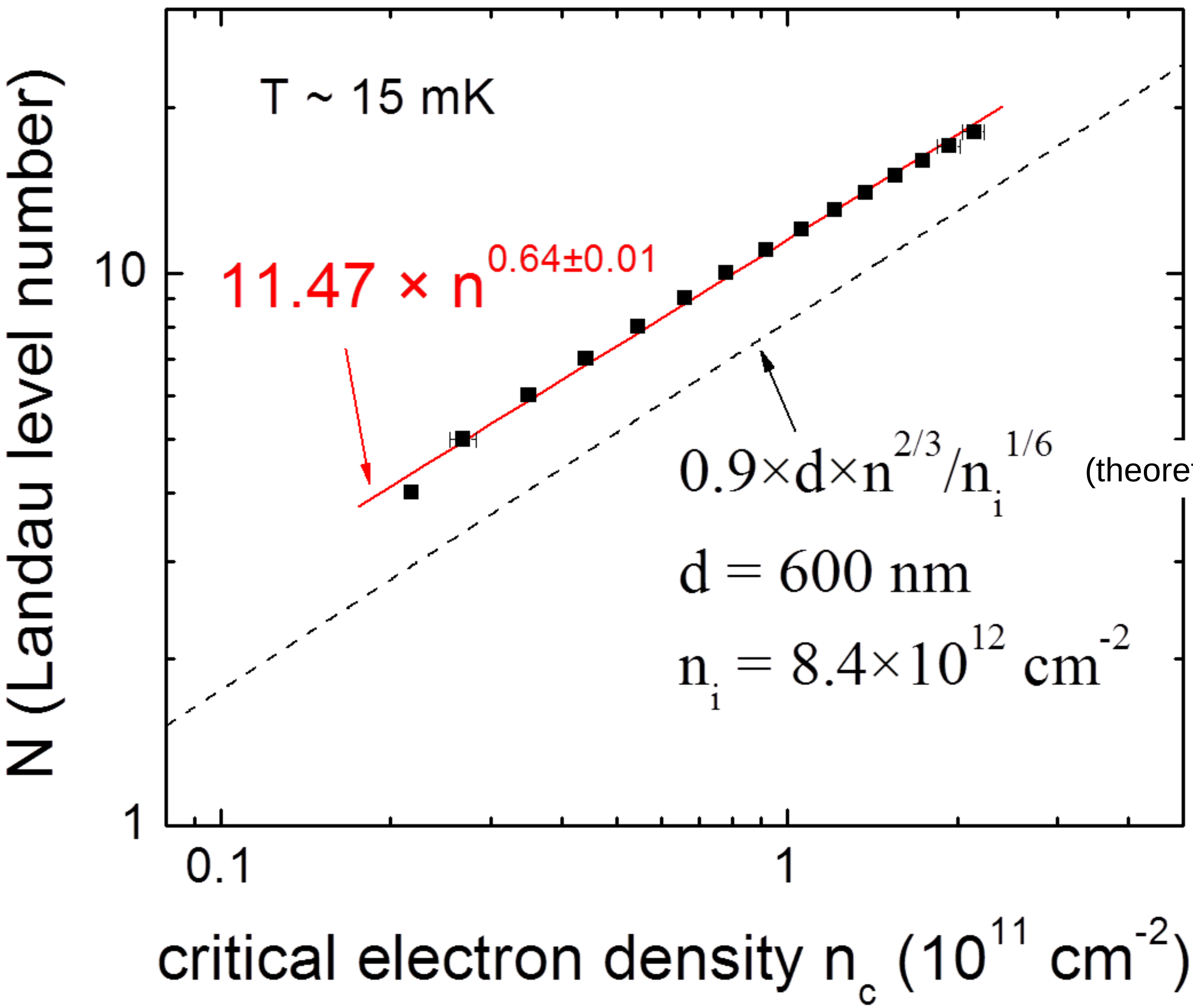
Kane, Pfeiffer, West, and Harnett, APL,1993



B = 0.197T
T ~ 15 mK
R_xx
10
1
0.1
0.01
ν=2
3
5
7
ν=29
30
32
40
0.0
0.5
1.0
1.5
2.0
electron density (10^11 cm^-2)



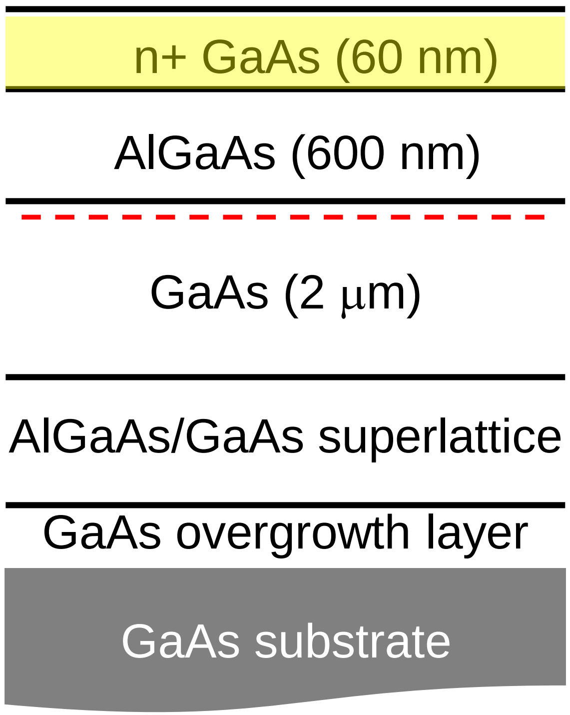
17
23
29
T ~ 15 mK
B=0.197T
B=0.165T
B=0.133T
R_xx (arb. units)
10
15
20
25
30
35
40
Landau Level Filling Factor ν

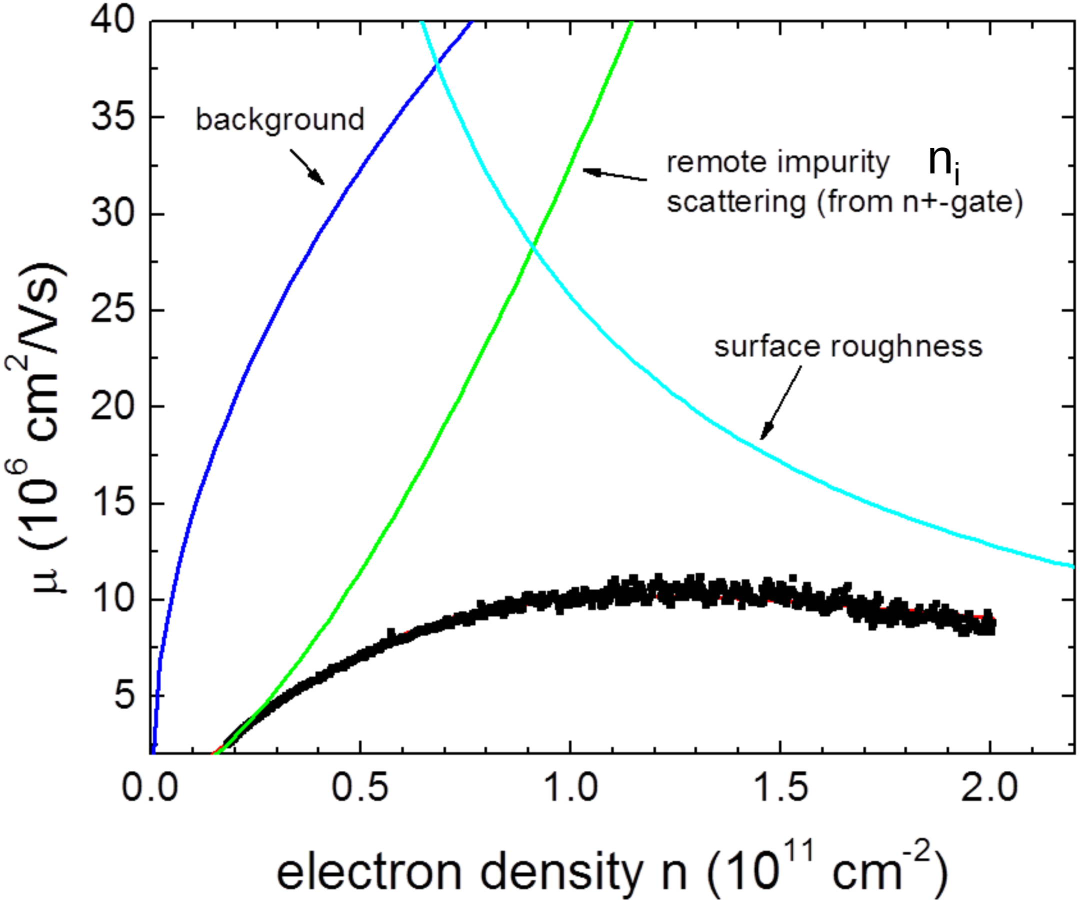


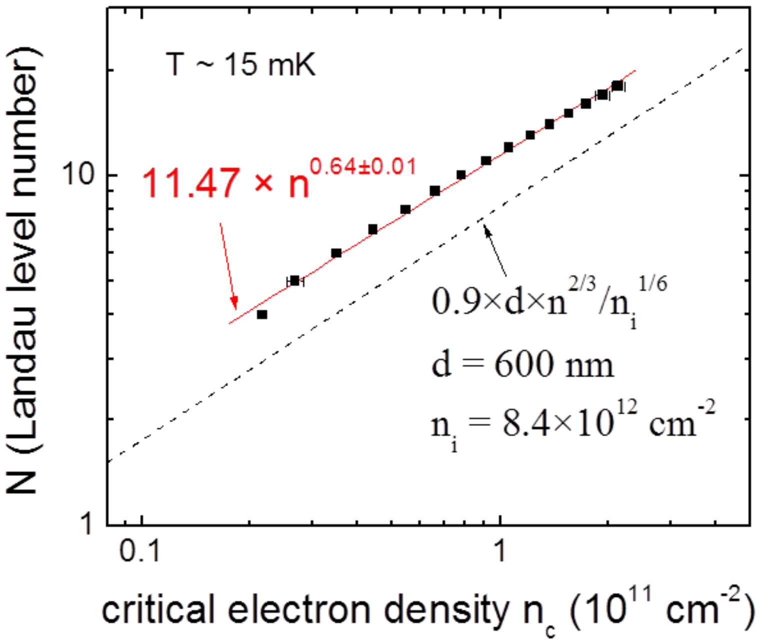
ν=2N+1

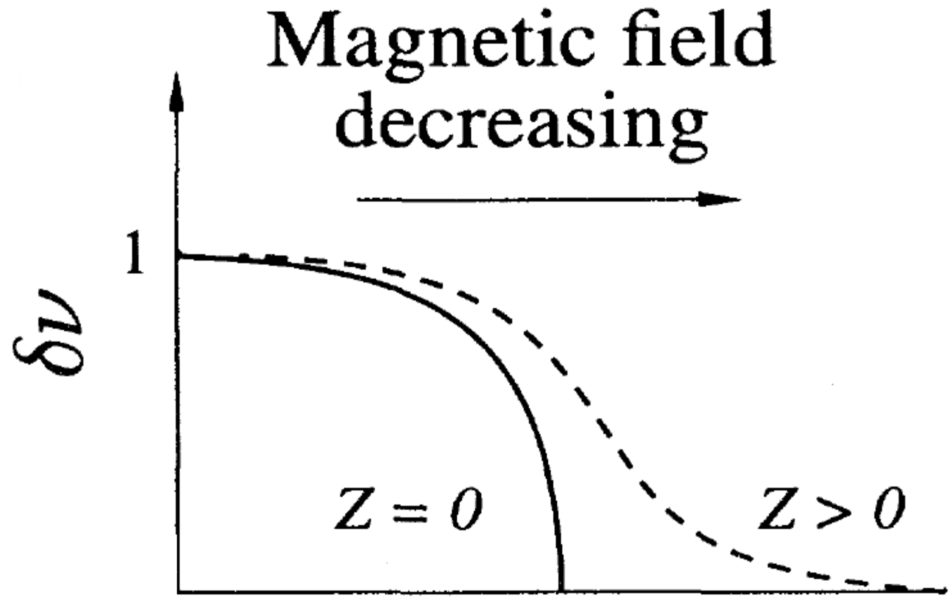
(theoretical prediction)

Pan et al, PRB (2011)


n+ GaAs (60 nm)
AlGaAs (600 nm)
GaAs (2 μm)
AlGaAs/GaAs superlattice
GaAs overgrowth layer
GaAs substrate


background
remote impurity scattering (from n+-gate)
n_i
surface roughness
μ (10^6 cm^2/Vs)
electron density n (10^{11} cm^{-2})
40
35
30
25
20
15
10
5
0.0
0.5
1.0
1.5
2.0





Fogler and Shklovskii [PRB **52**, 17366 (1995)]

part II conclusion

In a high-quality HIGFET, the Landau level number *N* follows a power-law dependence on the 2DEG electron density n, where the spin splitting collapses.

$N = 11.47 \times n^{0.64 \pm 0.01}$

This power-law dependence is in a good agreement with the theoretical prediction in the low-density regime.

Thank you for your attention