SAND2016-2554C

Emergence of Dirac Composite Fermions at the Half-Filled Landau Level of the Fractional Quantum Hall Effect

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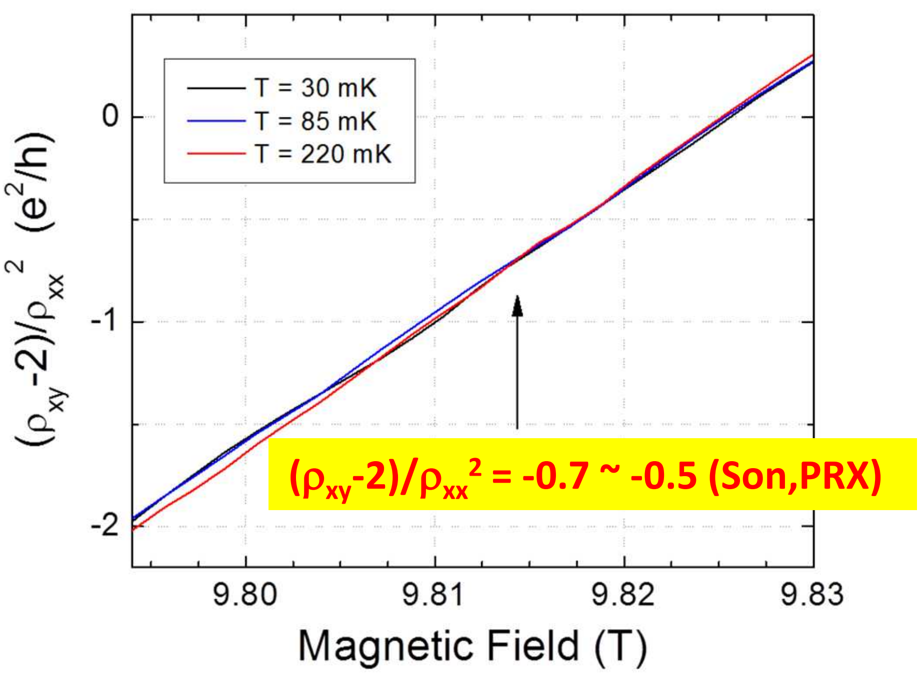
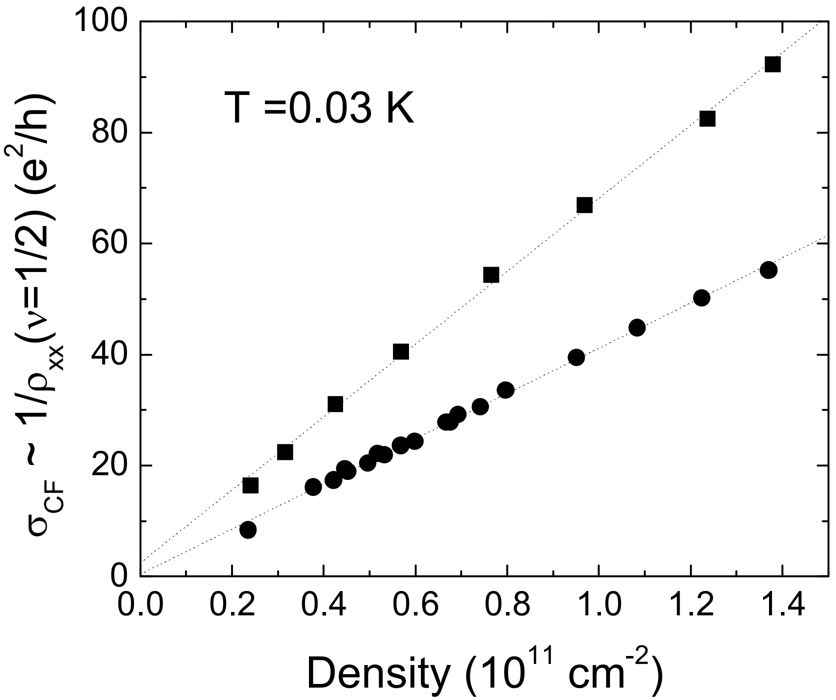
Main result – CFs are probably Dirac fermions

resistivity scaling



linear density dependence

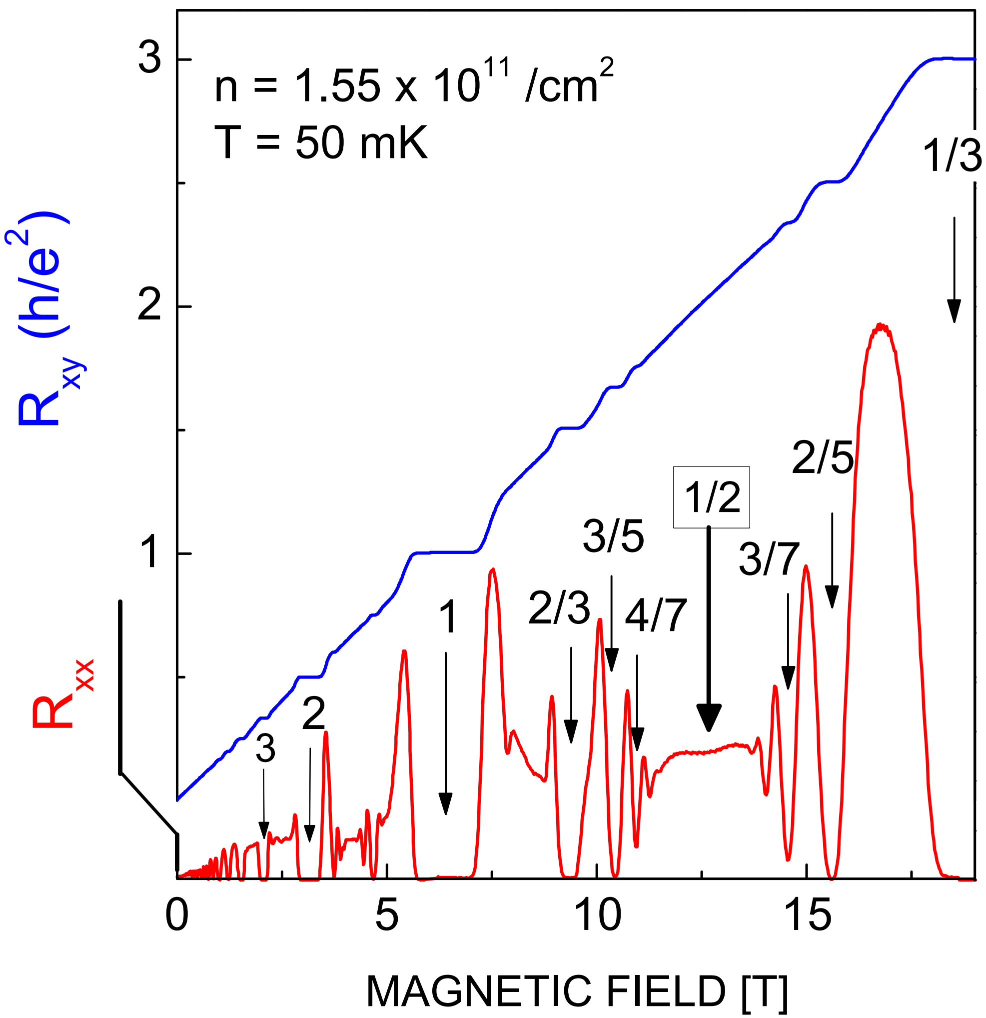


samples and measurements

Outline:

- Introduction
- Resistivity scaling at ν=1/2
- Density dependence of the CF conductivity

Quantum Hall effects

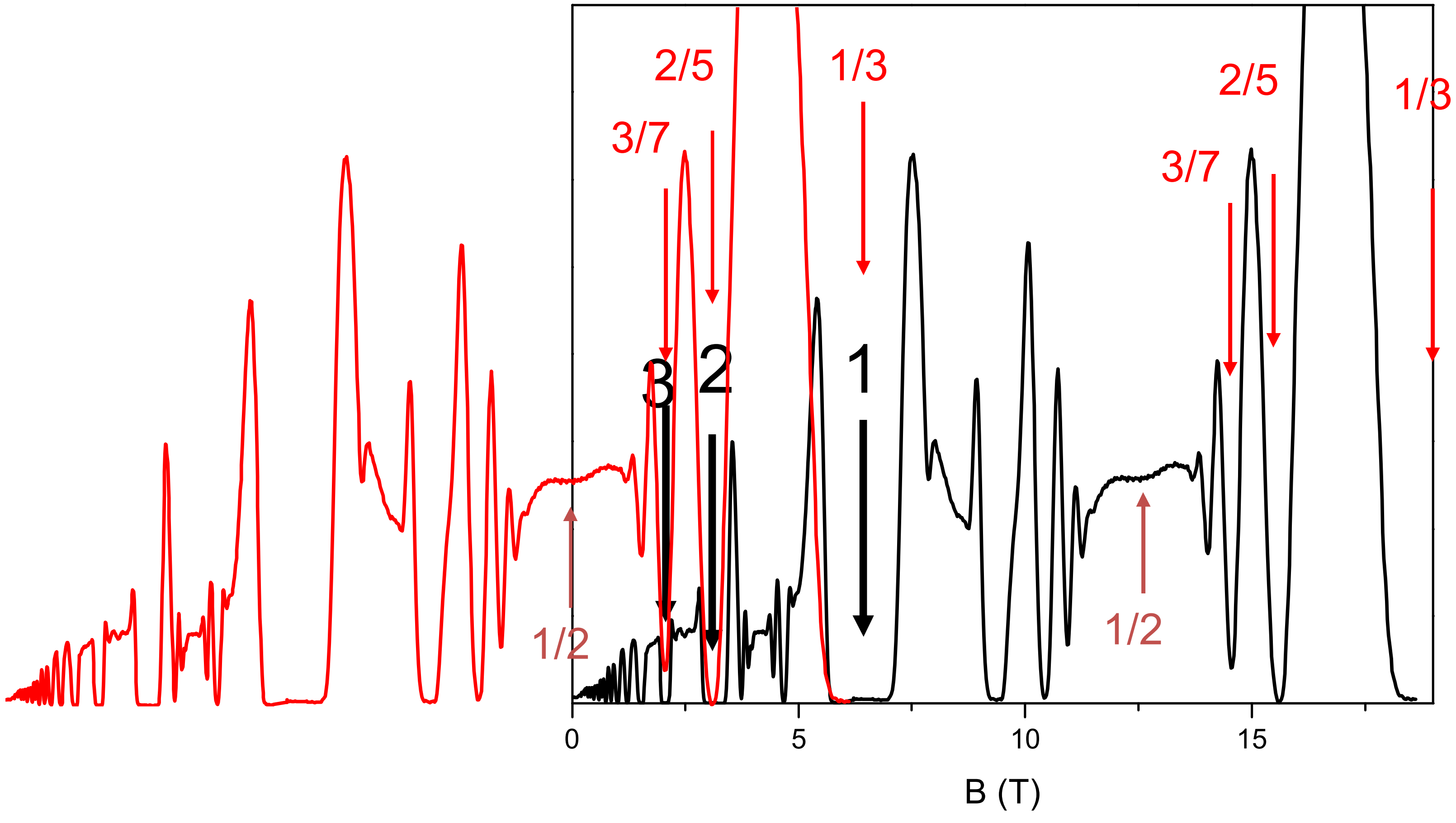


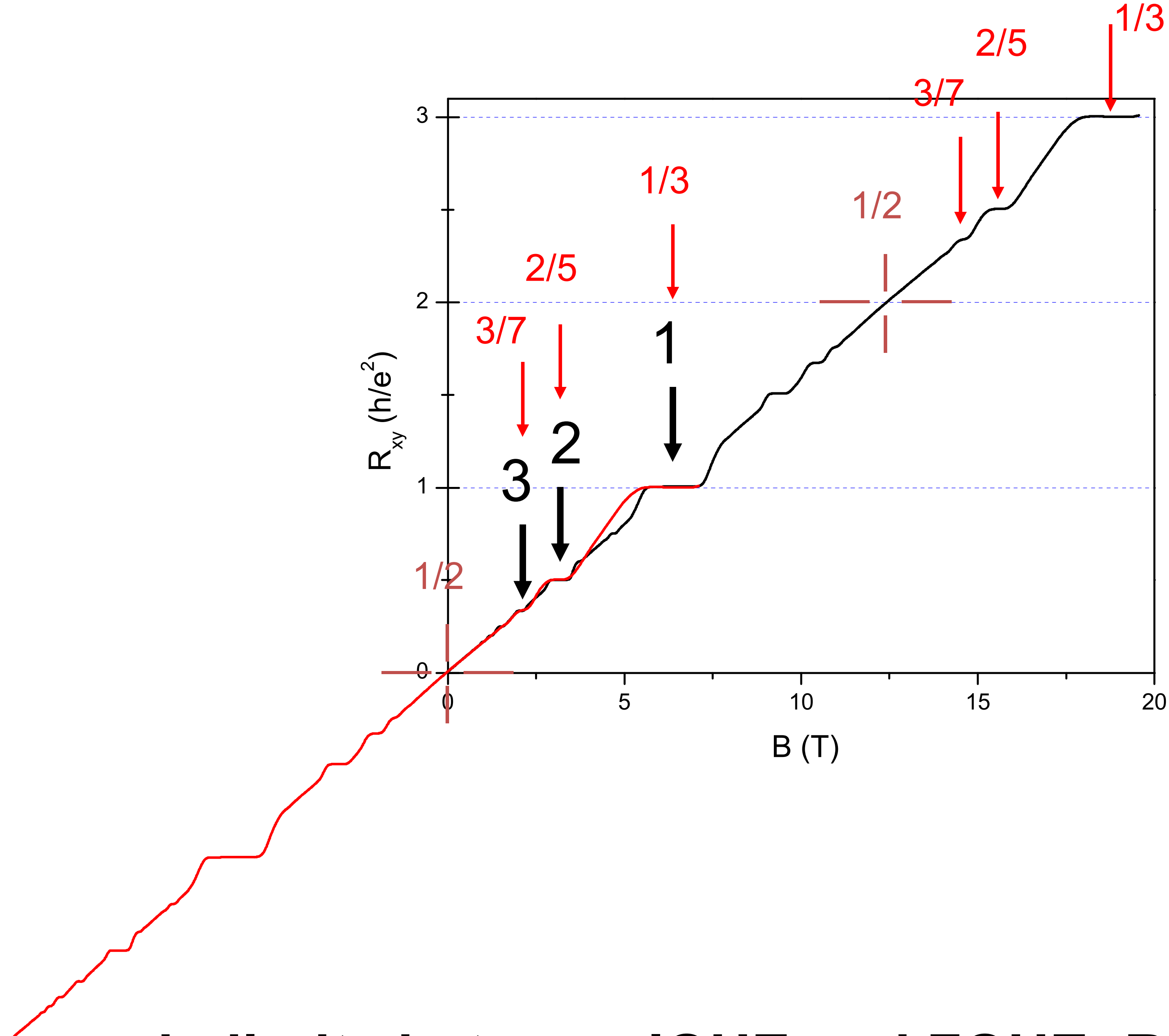
$R_{xy}=(h/e^2)/\nu$

IQHE – single particle
ν = 1, 2, 3 …

FQHE – many-body
ν= 1/3, 2/5, 3/7 ...
2/3, 3/5, 4/7 ...

similarity between IQHE and FQHE: R_{xx}



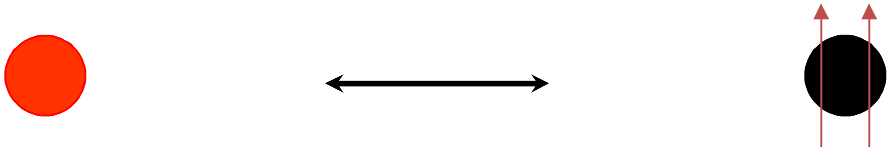


similarity between IQHE and FQHE: R_{xy}

Composite Fermion (CF) Model

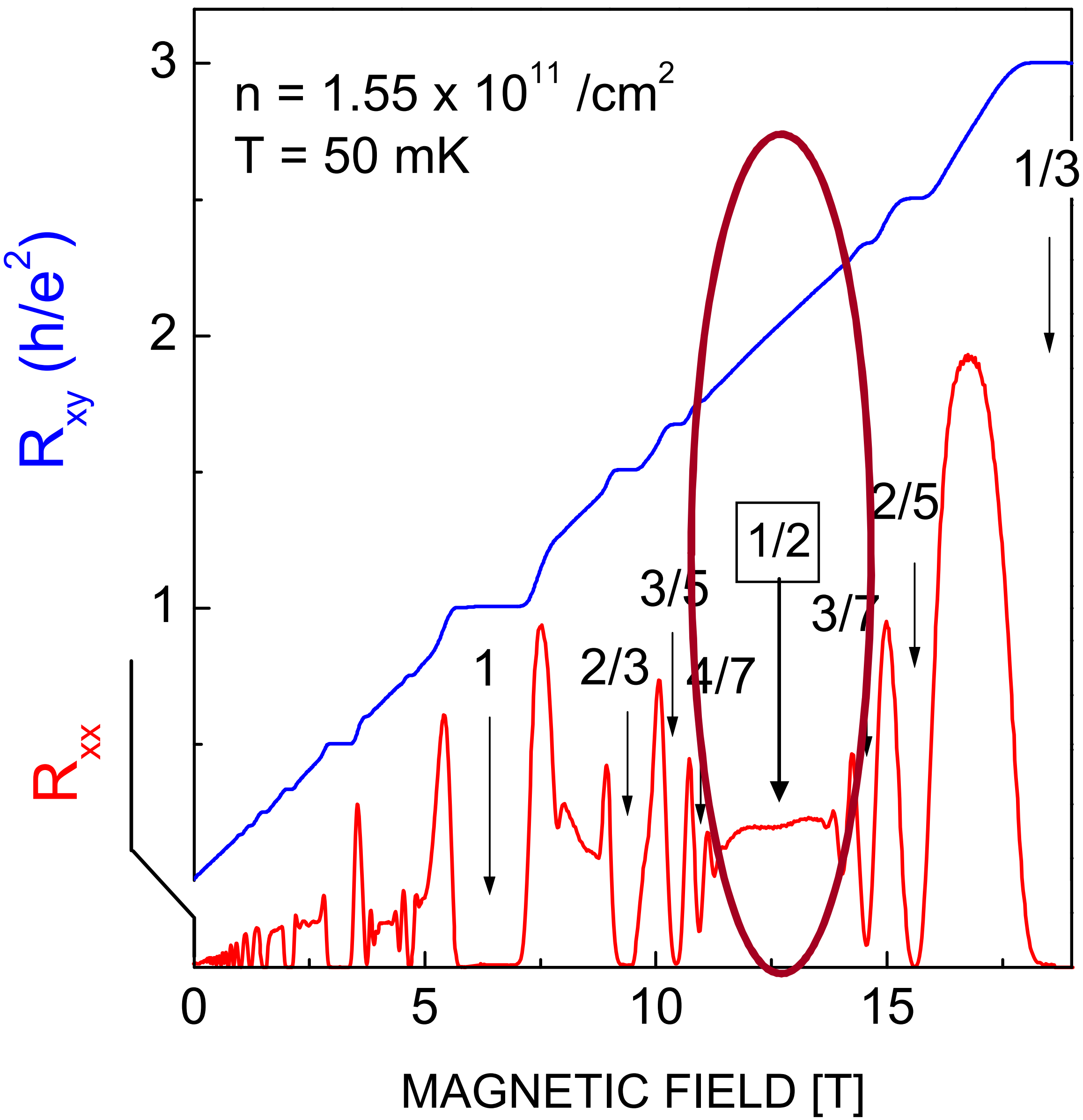
Jain, PRL 1989
Halperin, Lee, and Read (HLR), PRB 1993

one composite fermion = one electron + 2 flux quanta



$$B_{eff} = B - 2\Phi_0 \times n = B - 2nh/e = B - B_{1/2}$$

Classical transport features around ν=1/2



ν = 1/2

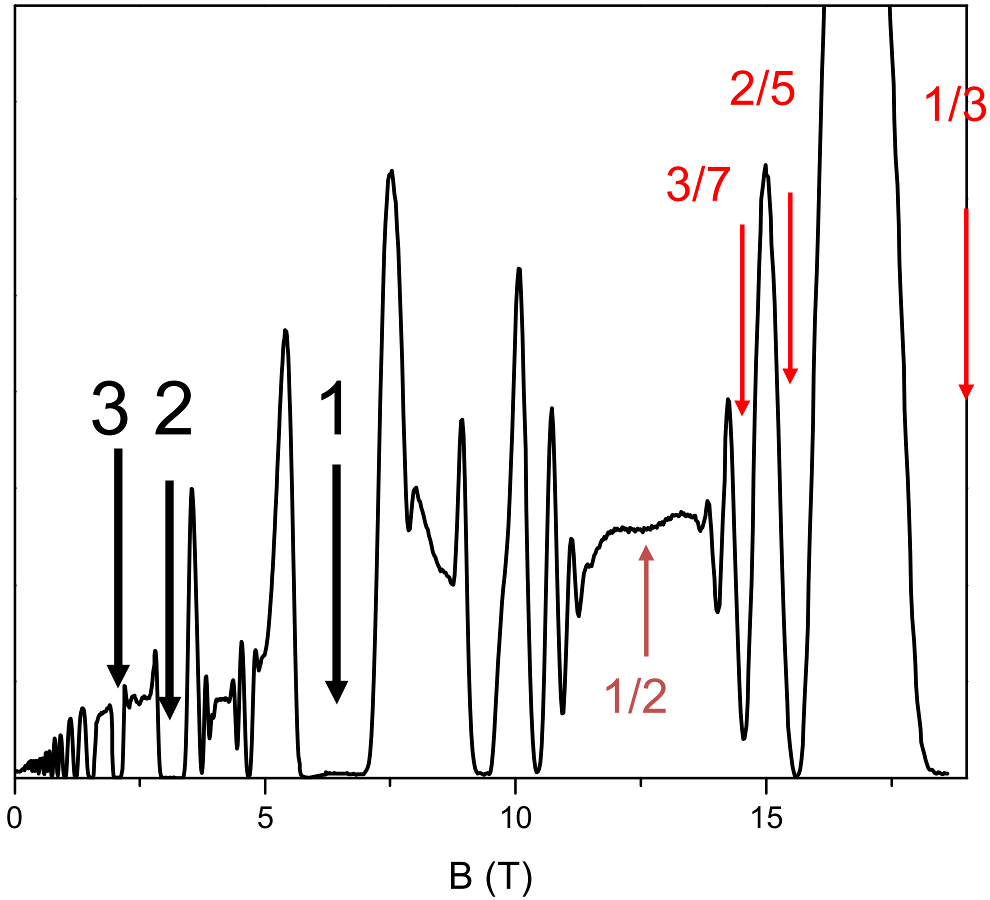
$B_{eff} = B - B_{1/2} = 0$

CFs form fermi sea

IQHE of CF FQHE of e^-

p	$\nu = p/(2p+1)$
1	1/3
2	2/5
3	3/7

....



Lots of Fractions Observed

1/3	1/5	1/7	1/9	2/11	2/13	2/15	2/17	3/19	5/21	6/23
2/3	2/5	2/7	2/9	3/11	3/13	4/15	3/17	5/19	10/21	6/25
4/3	3/5	3/7	4/9	4/11	4/13	7/15	4/17	9/19		
5/3	4/5	4/7	5/9	5/11	5/13	8/15	5/17	10/19		
7/3	6/5	5/7	7/9	6/11	6/13	11/15	6/17			
8/3	7/5	9/7	11/9	7/11	7/13	22/15	8/17			
	8/5	10/7	13/9	8/11	10/13	23/15	9/17			
	9/5	11/7	14/9	16/11	19/13					
	11/5	12/7		17/11	20/13					
	12/5									
	13/5									
	14/5									

Unclarified aspects of CF theory

……

The most fundamental problem is the lack of particle-hole symmetry

(copied from Son's presentation at the workshop on Strongly Interacting Topological Phases)

Kivelson, Lee, Krotov, and Gan, PRB (1997).
Lee, PRL (1998).
Kamburov et al. PRL (2014).
Barkeshli, Mulligan, and Fisher, PRB (2015).
Balram, Toke, and Jain, PRL (2015).
Murthy and Shankar, arXiv: 1508.06974.

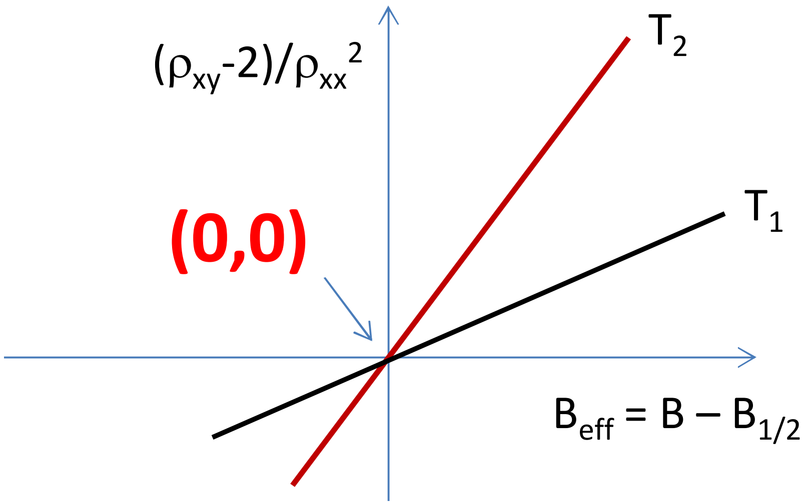
Dirac composite fermions

Son, *Phys. Rev. X* **5**, 031027 (2015); Metlitski and Vishwanath, arXiv:1505.05142; Wang and Senthil, arxiv:1507.08290; Geraedts et al, arXiv:1508.04140; …

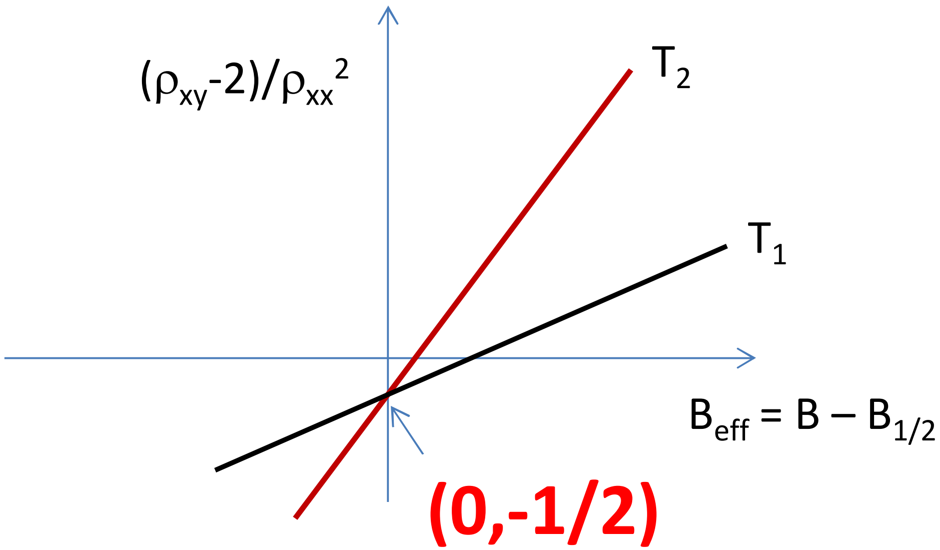
$$\frac{\rho_{xy} - 2}{\rho_{xx}^2} = \tilde{\sigma}_{xy} - \frac{1}{2}$$

Son, PRX (2015).

HLR CFs: $(\rho_{xy}-2)/\rho_{xx}^2 = 0$



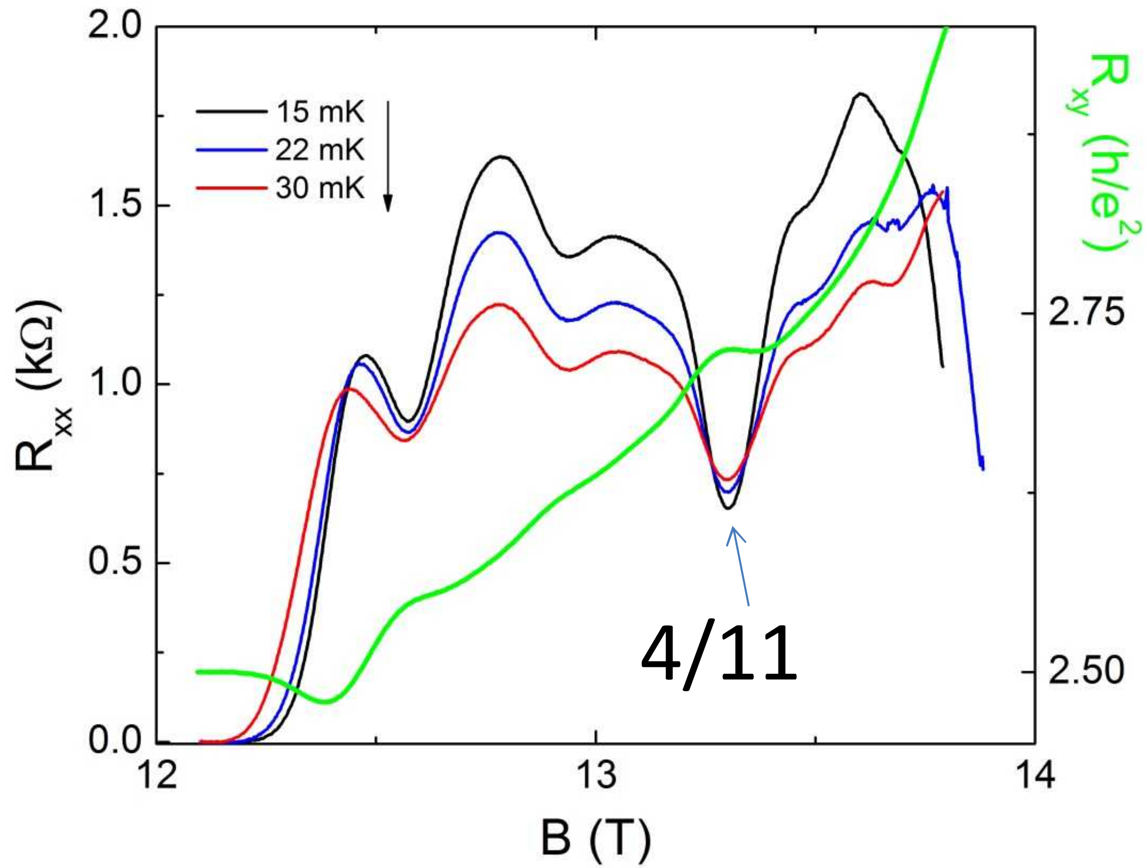
Dirac CFs: $(\rho_{xy}-2)/\rho_{xx}^2 = -1/2$



D.T. Son, *Is the Composite Fermion a Dirac Particle? Phys. Rev. X* **5**, 031027 (2015).

Note that, because of the smallness of ρ_{xx}, distinguishing Berry phases of 0 and π requires a sufficiently accurate measurement of ρ_{xy}: For a relatively large $\rho_{xx} \sim 0.1h/e^2$, an accuracy better than $5 \times 10^{-3}h/e^2$ is needed.

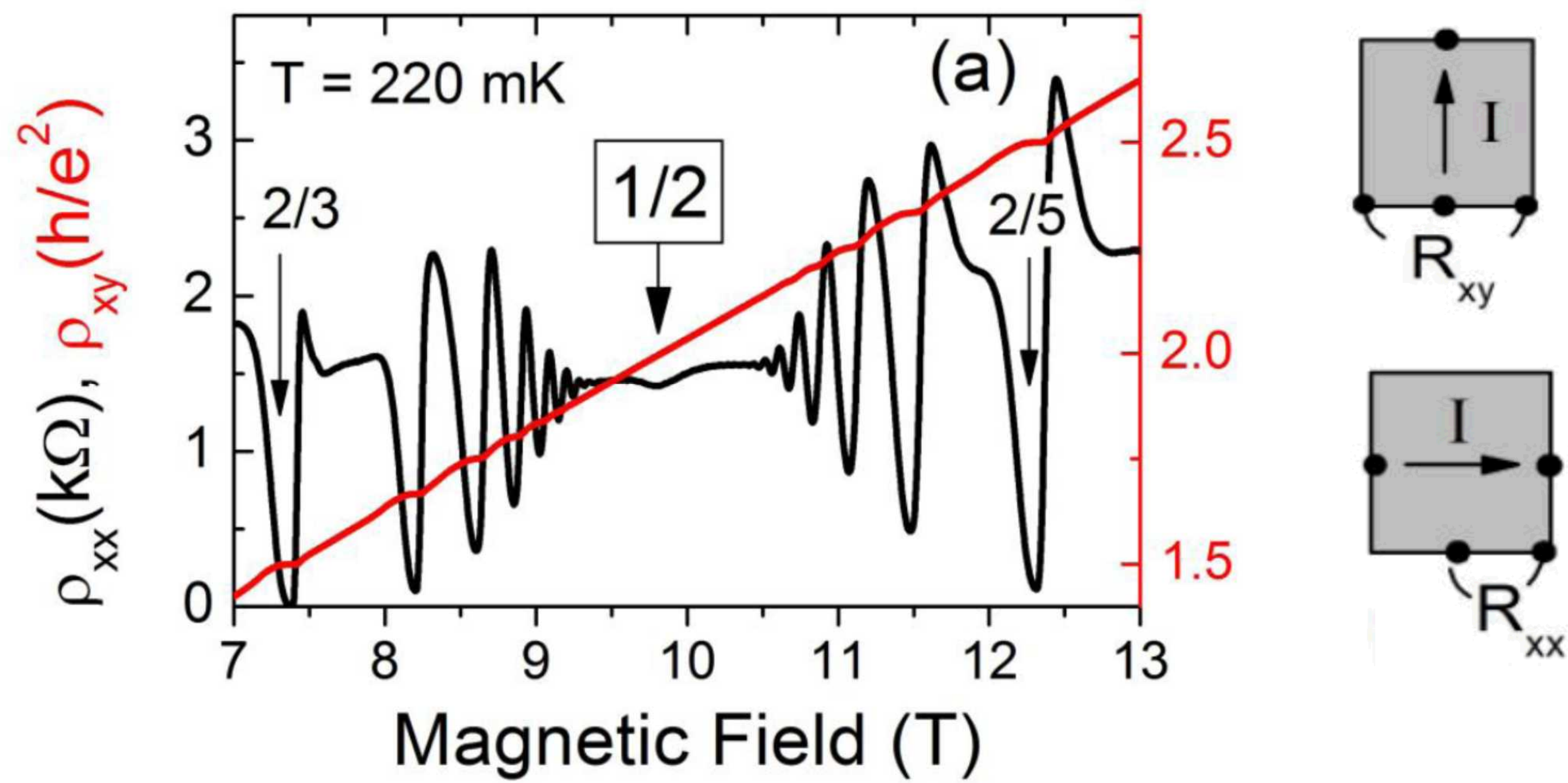
Sample: high quality quantum well



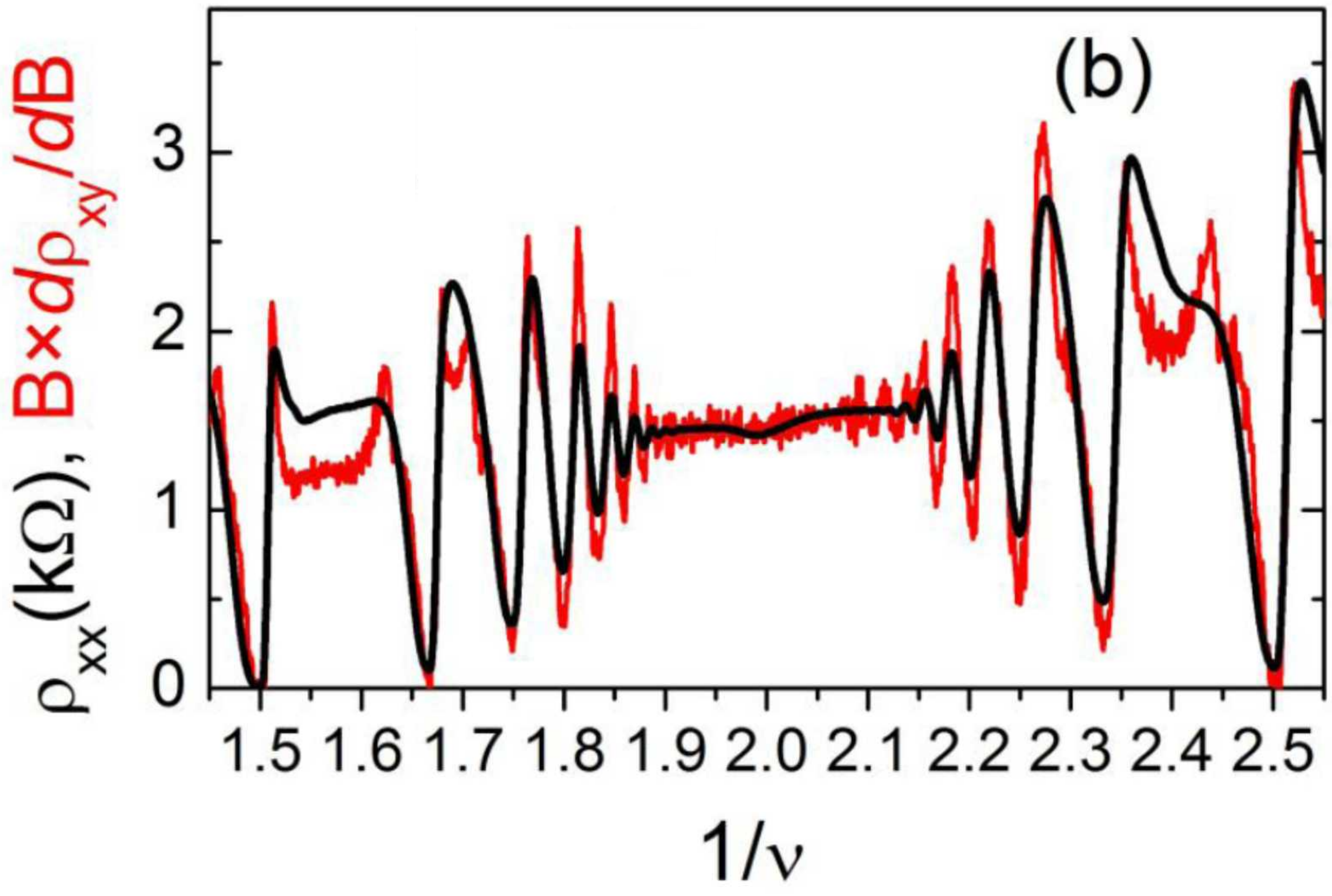
PRL (2003)
PRB (2015)

Density: $n = 1.190 \times 10^{11}$ cm^{-2}
Mobility: $\mu \sim 13 \times 10^{6}$ cm^{2}/Vs

Magneto-transport measurements around ν=1/2

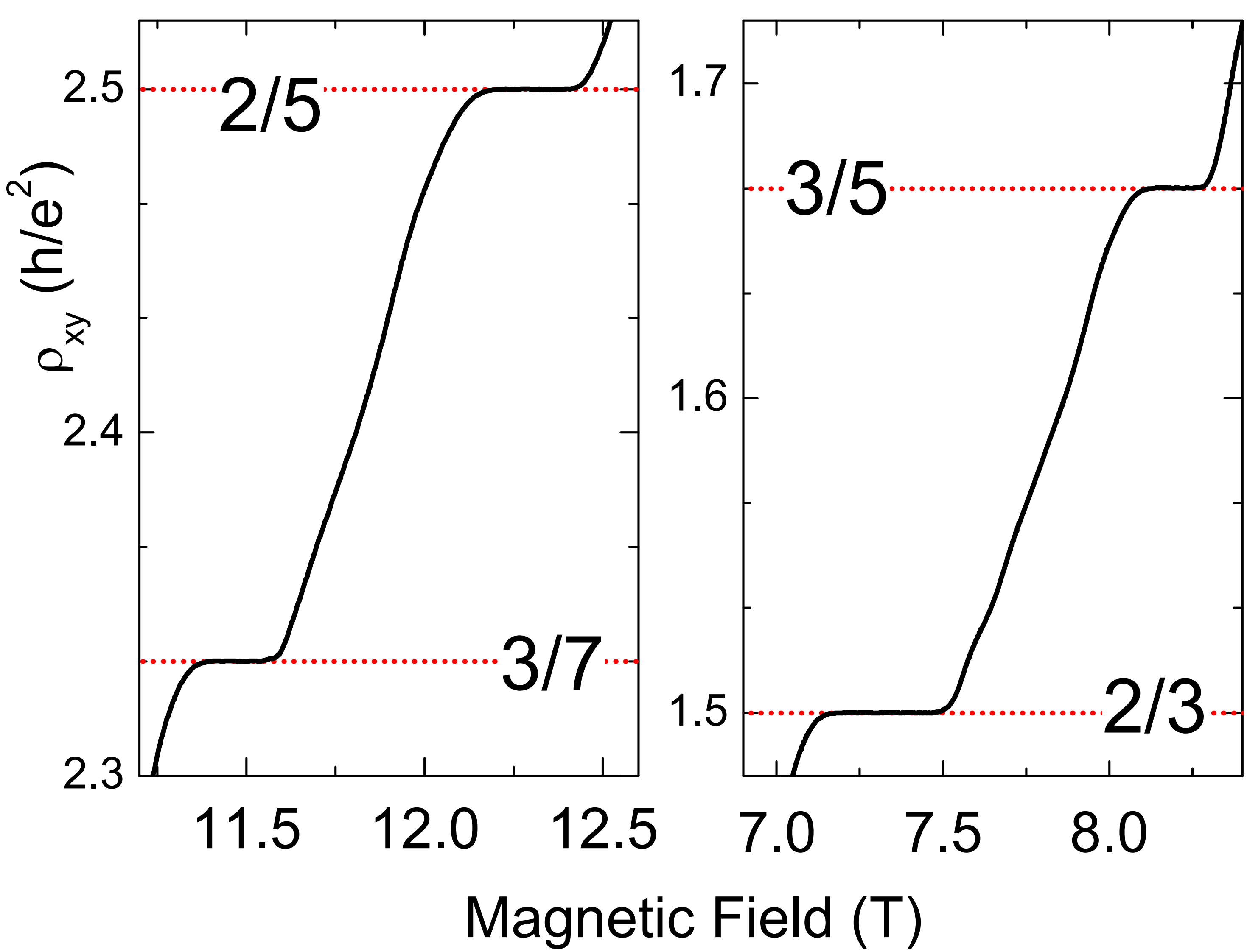


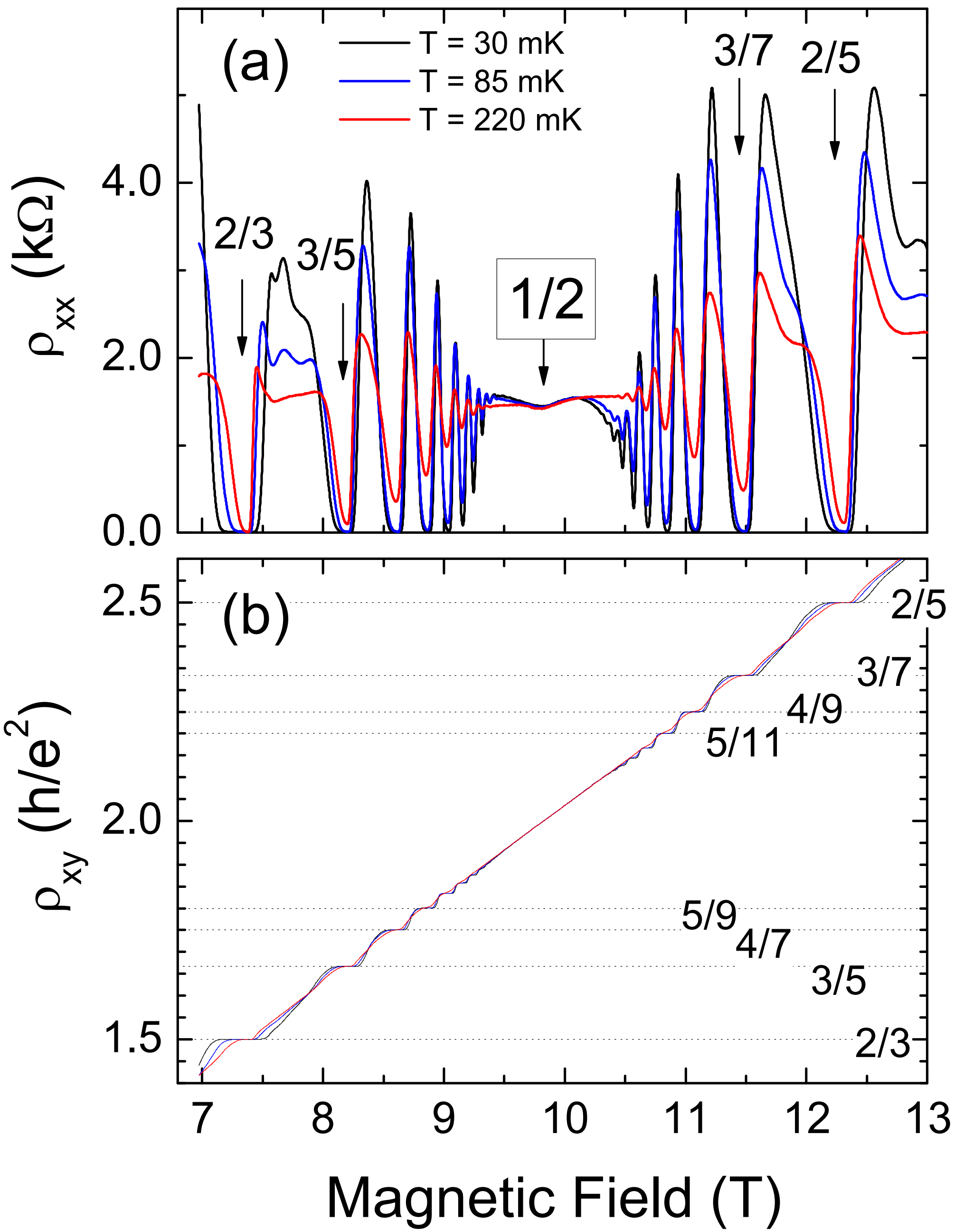
Highly uniform 2DEG



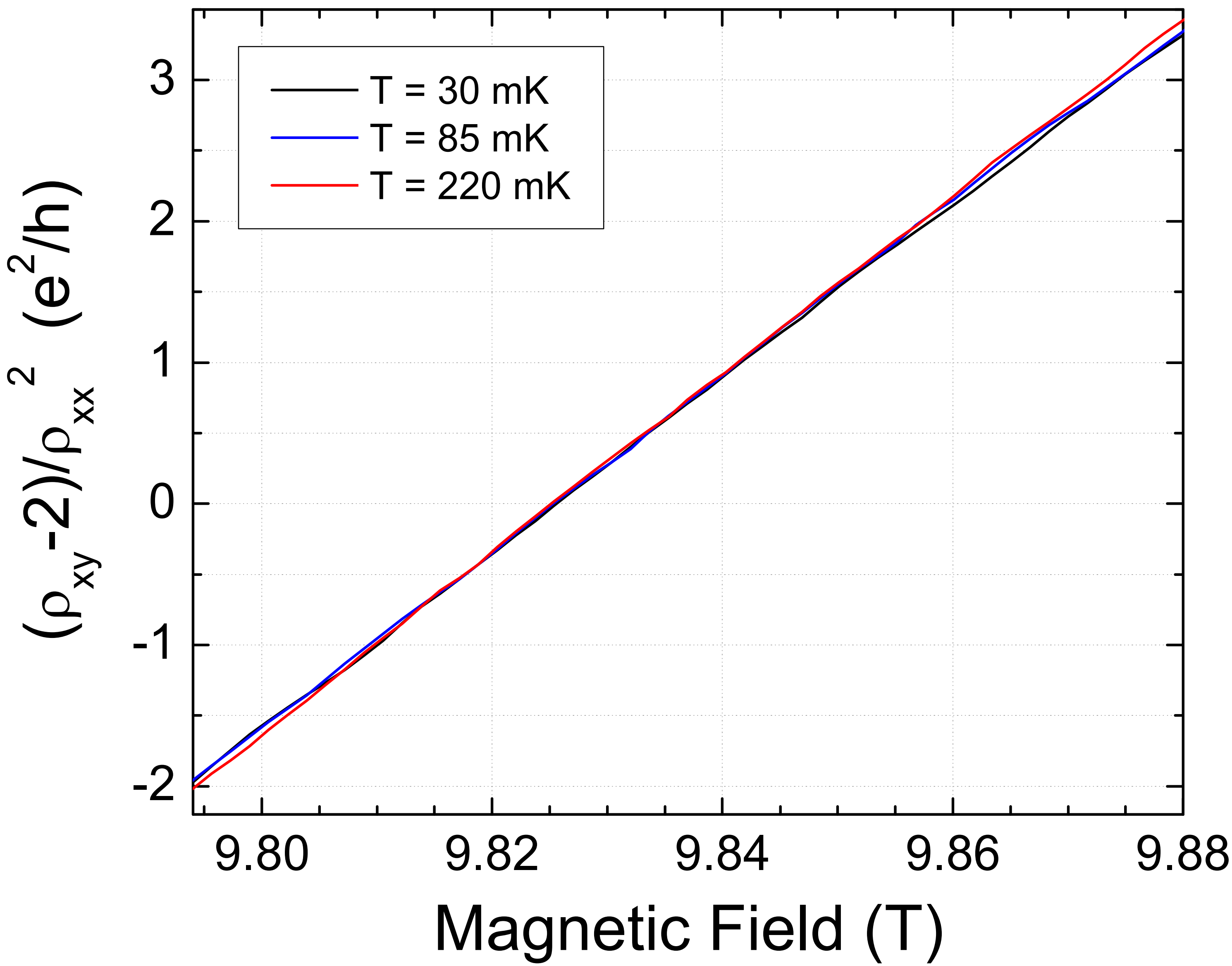
Accurate Hall resistivity

Quantization better than 0.1%

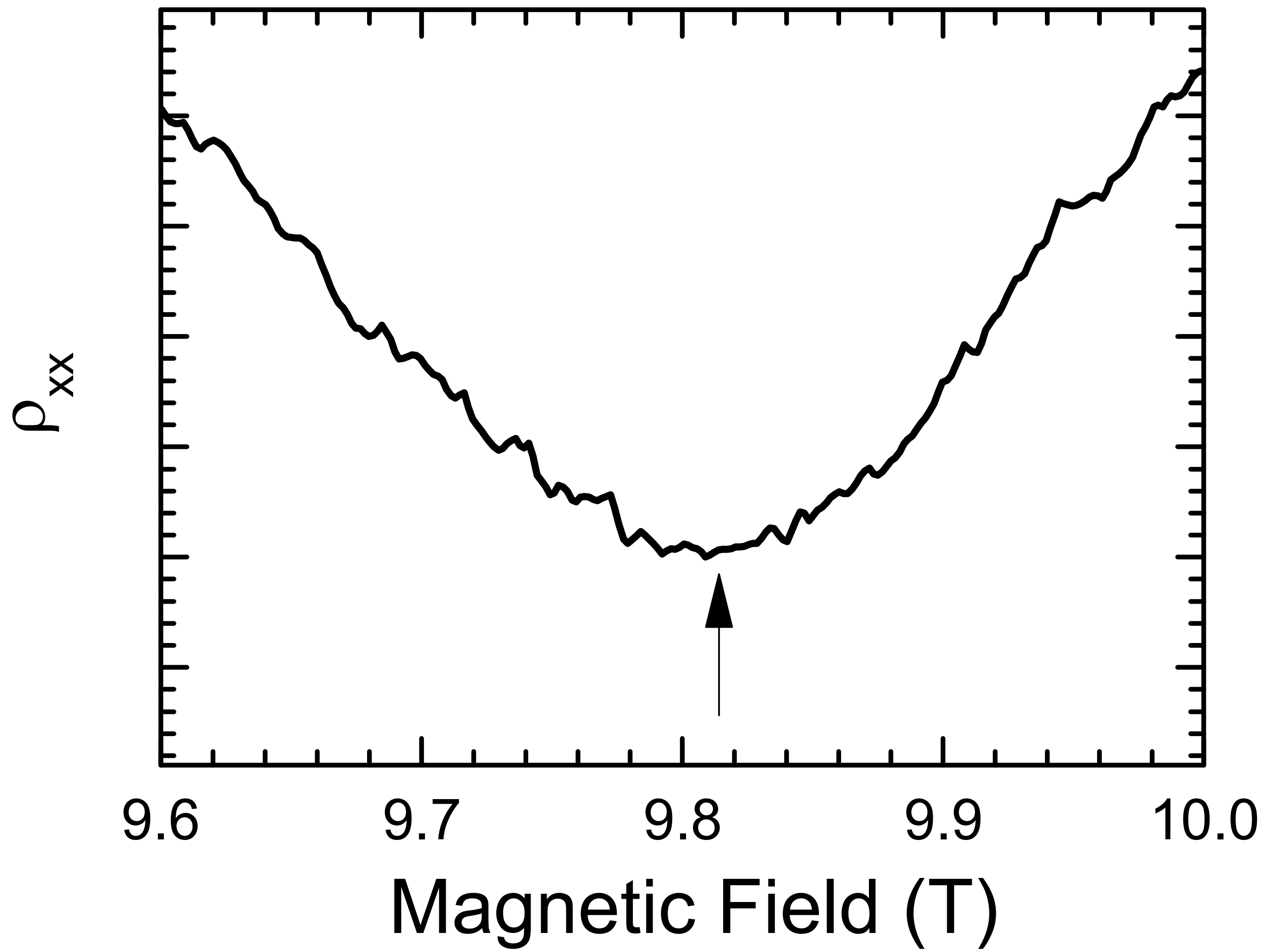


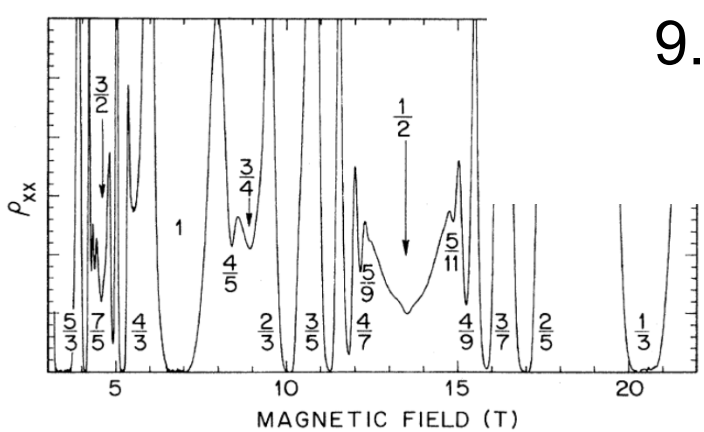


(a)
T = 30 mK
T = 85 mK
T = 220 mK
3/7
2/5
2/3
3/5
1/2
ρxx (kΩ)
4.0
2.0
0.0
(b)
2/5
3/7
4/9
5/11
5/9
4/7
3/5
2/3
ρxy (h/e2)
2.5
2.0
1.5
7
8
9
10
11
12
13
Magnetic Field (T)



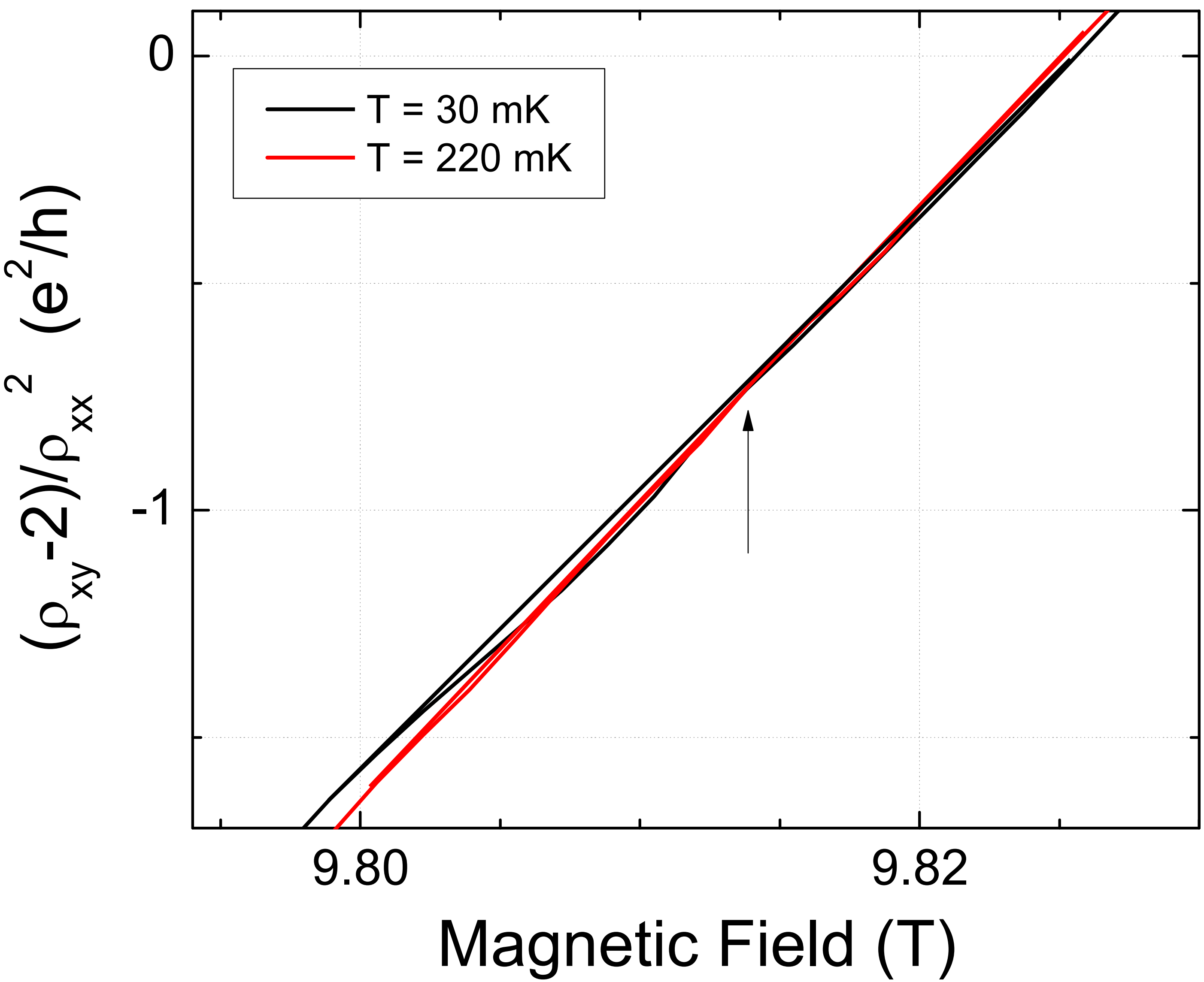
T = 30 mK
T = 85 mK
T = 220 mK
$(\rho_{xy}-2)/\rho_{xx}^2$ (e^2/h)
3
2
1
0
-1
-2
9.80
9.82
9.84
9.86
9.88
Magnetic Field (T)



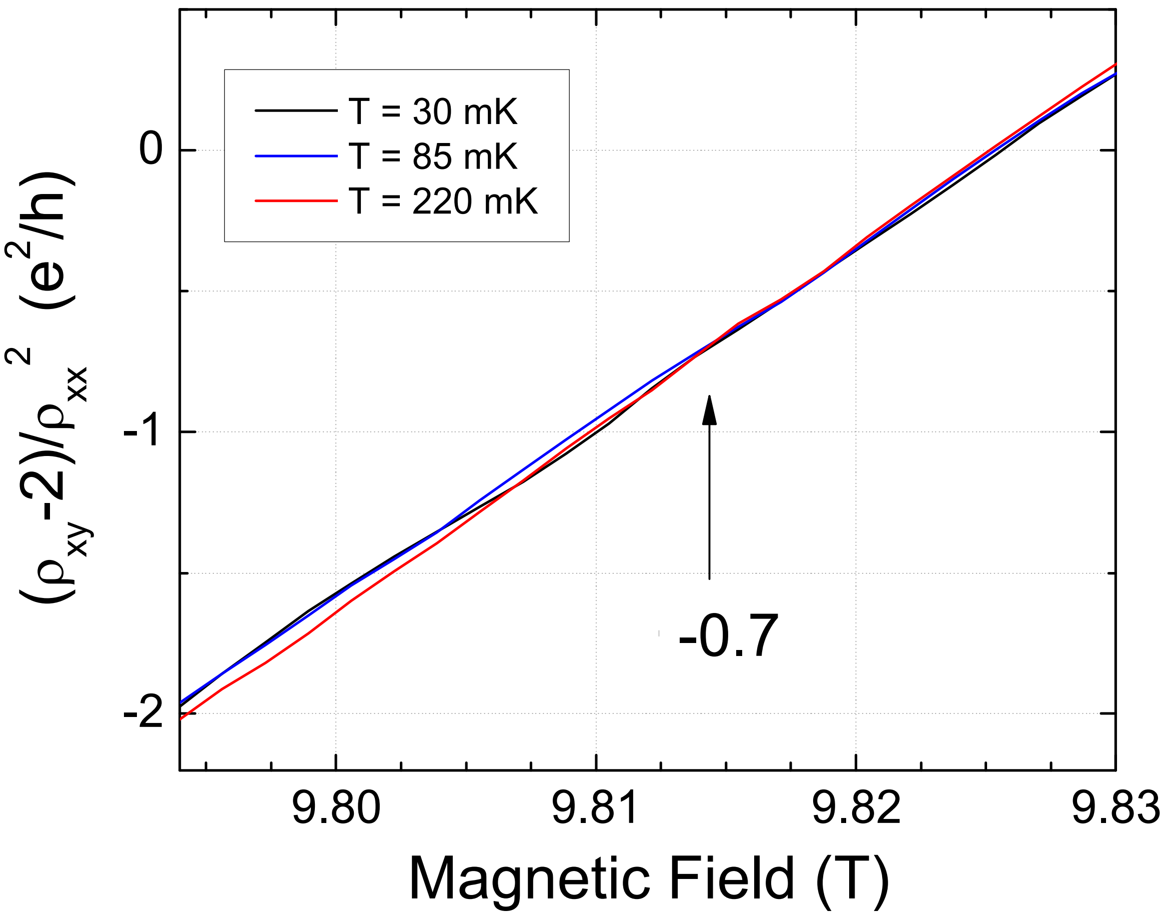


H.W. Jiang et al PRB (1989)

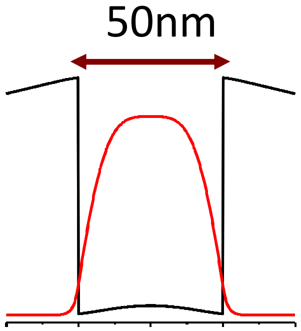
$B_{1/2} = 9.814\text{T}$



T = 30 mK
T = 220 mK
0
-1
9.80
9.82
Magnetic Field (T)
$(\rho_{xy}-2)/\rho_{xx}^2$ (e^2/h)



$$\frac{\rho_{xy} - 2}{\rho_{xx}^2} = -0.7$$



- Finite thickness
- Landau level mixing

$\kappa = e^2/\varepsilon l_B/\hbar\omega_c = 0.87$ at $\nu = 1/2$

Details …

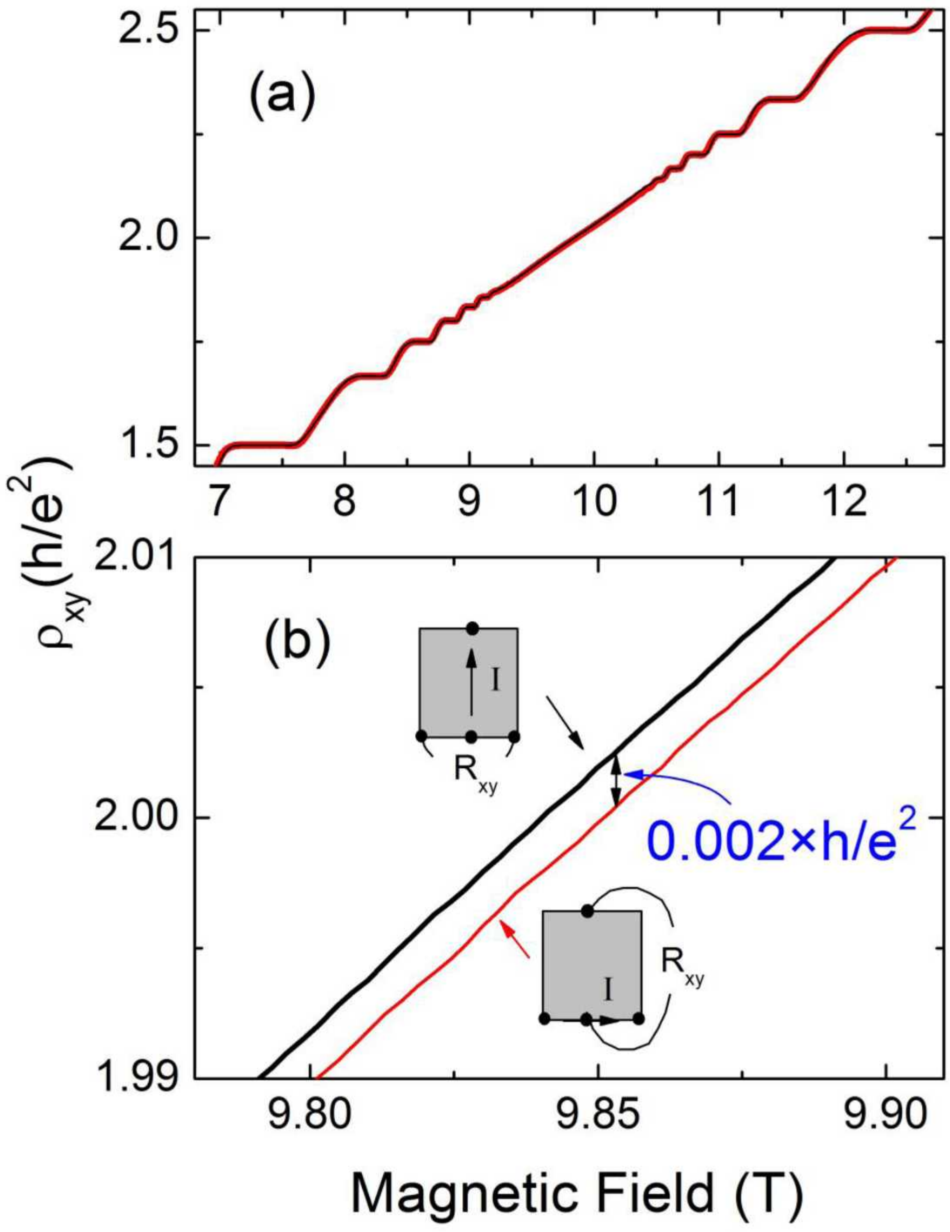
- Mixing of ρ_{xx} and ρ_{xy}

$$\rho_{xy} = \rho_{xy}{}^{0} + \alpha\rho_{xx}$$

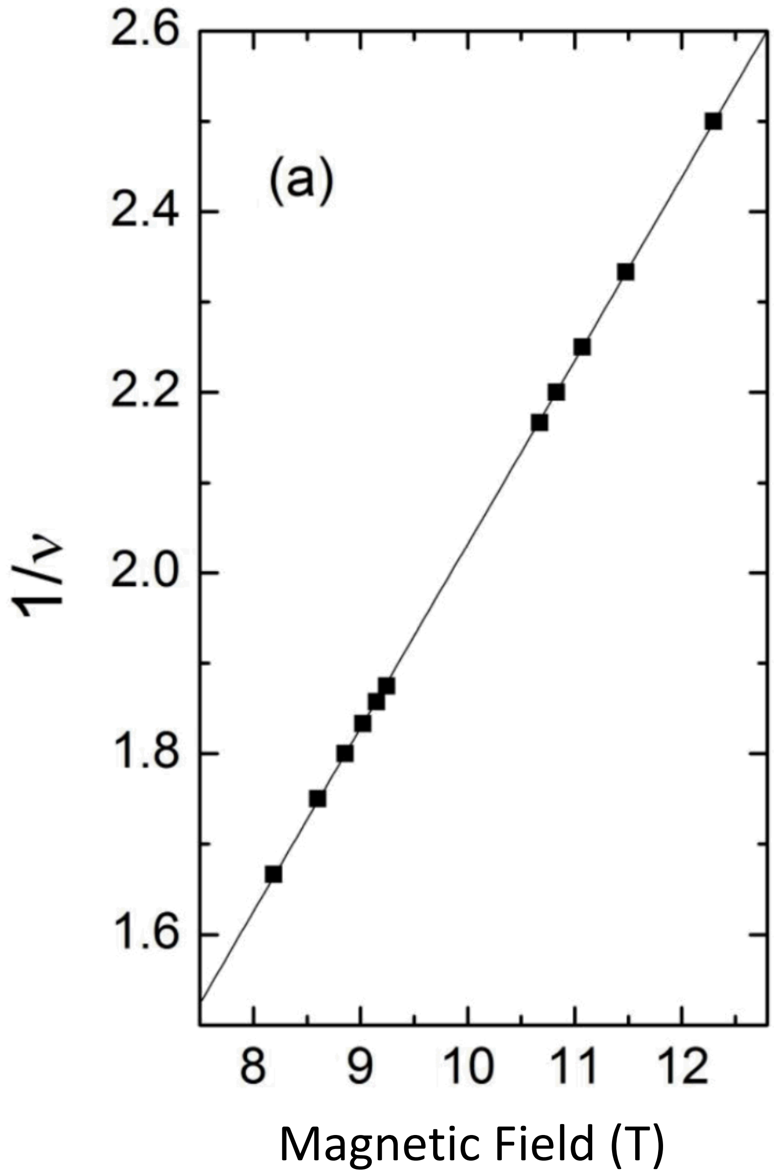
$$\rho_{xy}(+B) = \rho_{xy}{}^{0}(B) + \alpha\rho_{xx}(B)$$

$$\rho_{xy}(-B) = -\,\rho_{xy}{}^{0}(B) + \alpha\rho_{xx}(B)$$

$$\rho_{xy}{}^{0} = (\rho_{xy}(+B) - \rho_{xy}(-B))/2$$

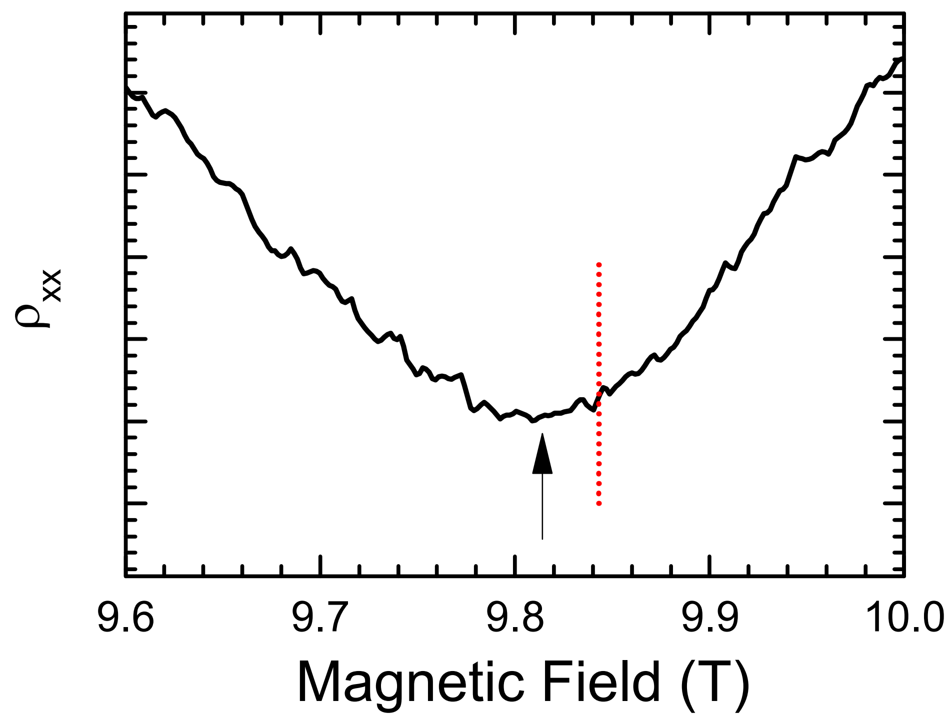


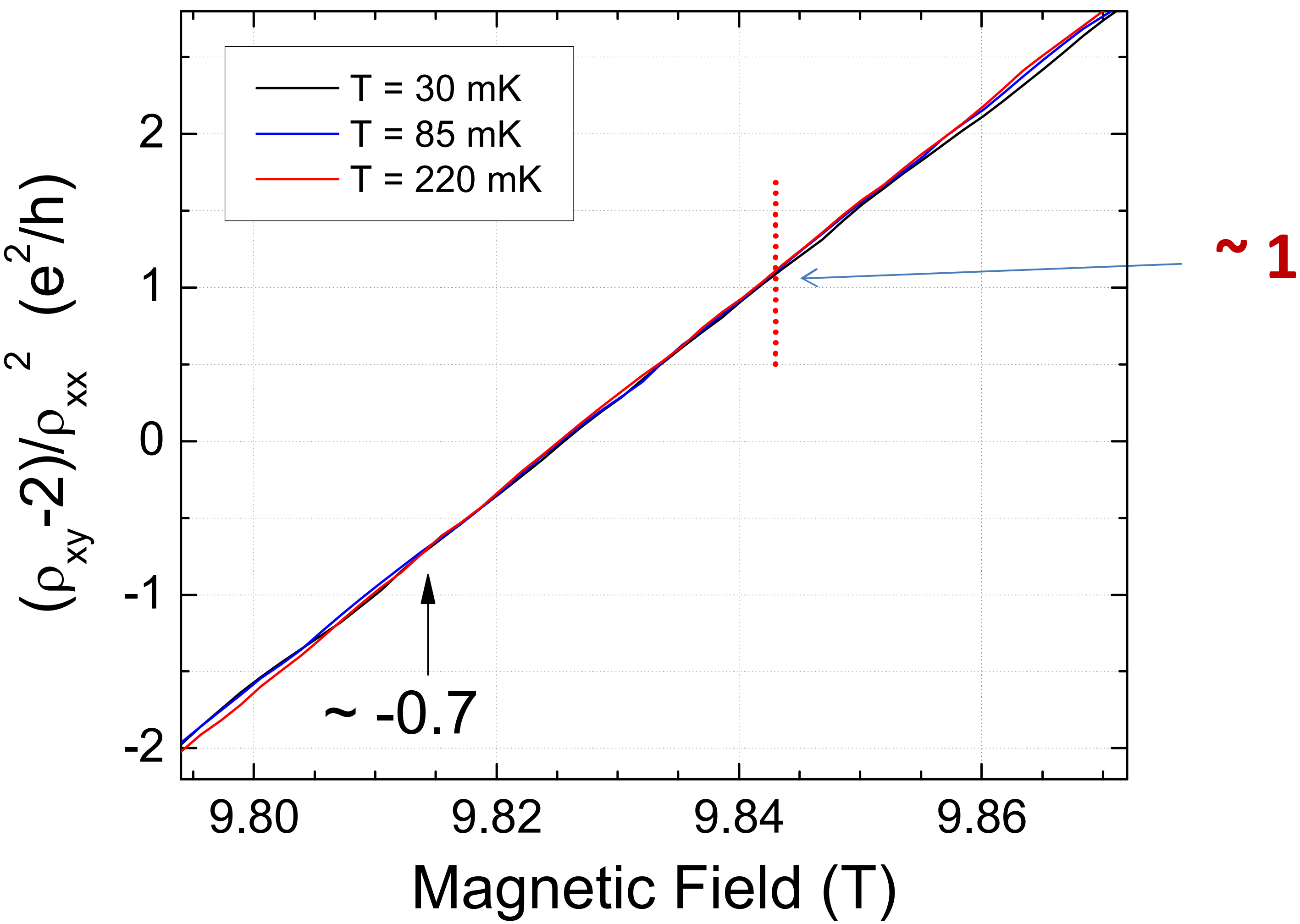
The position of the 1/2 state



straight line, through origin

$B_{\nu=1/2}$ = 9.843T





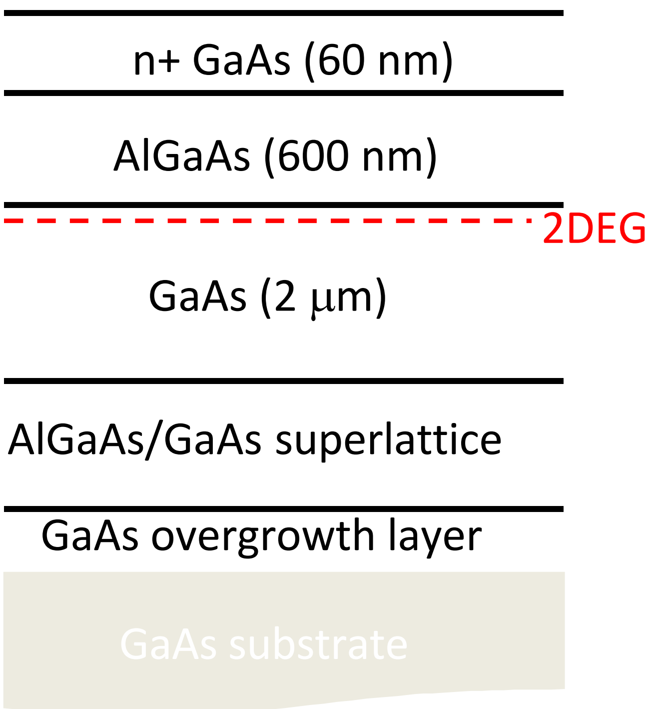
- Landau level mixing $\kappa = e^2/\varepsilon l_B/\hbar\omega_c = 0.87$ at $\nu = 1/2$

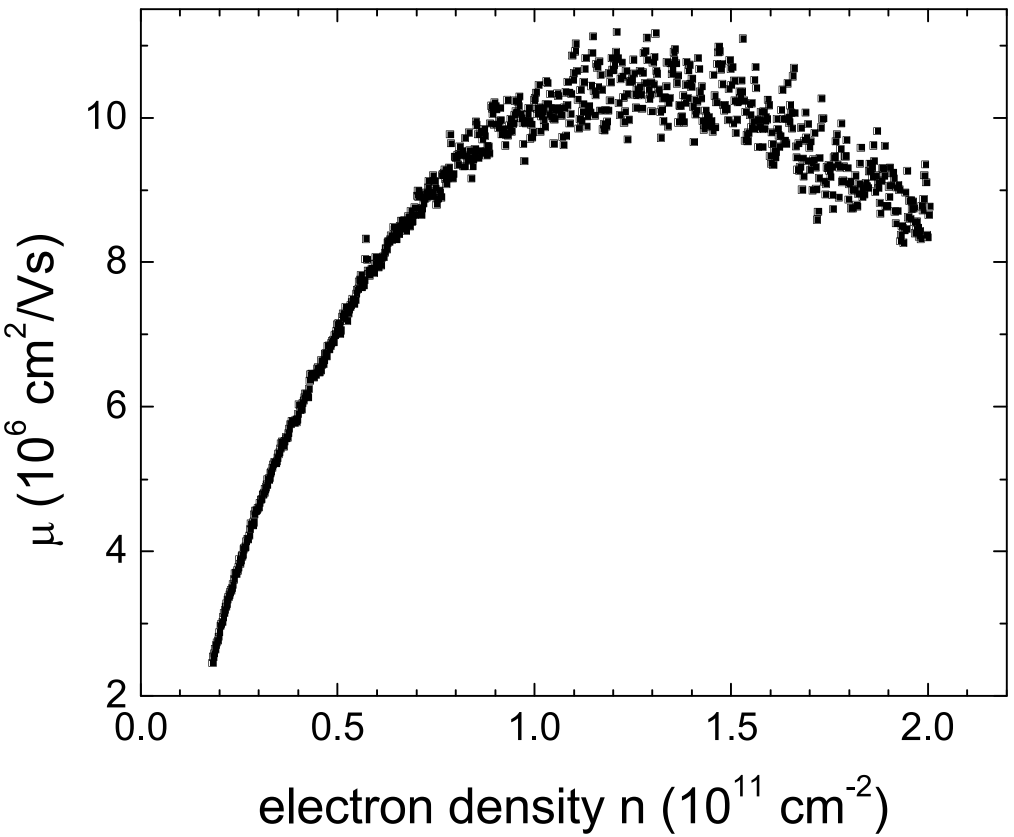
DENSITY DEPENDENCE OF CF CONDUCTIVITY

HIGFET

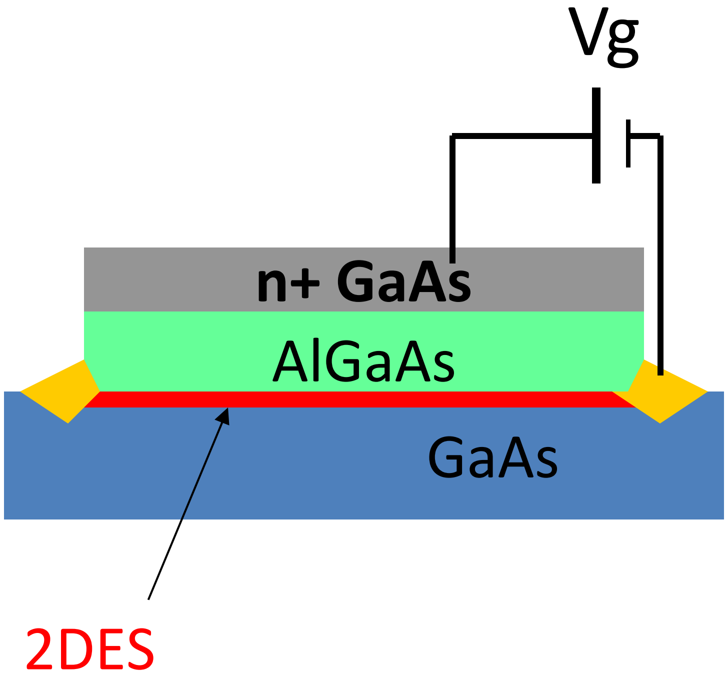
(Heterojunction-Insulated Gate Field-Effect Transistor)

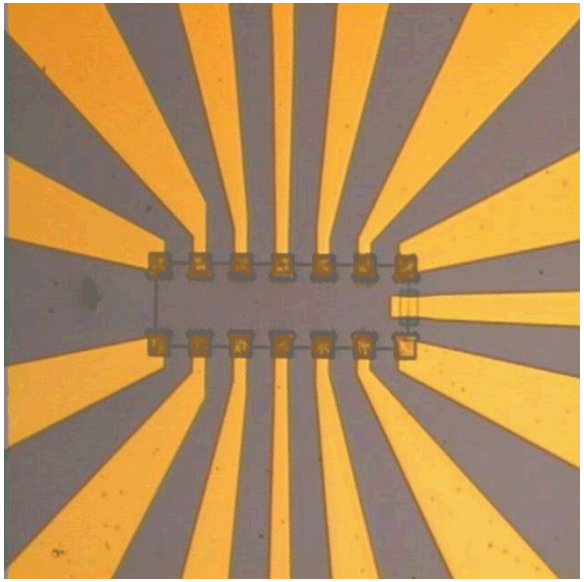
high mobility down to very low densities





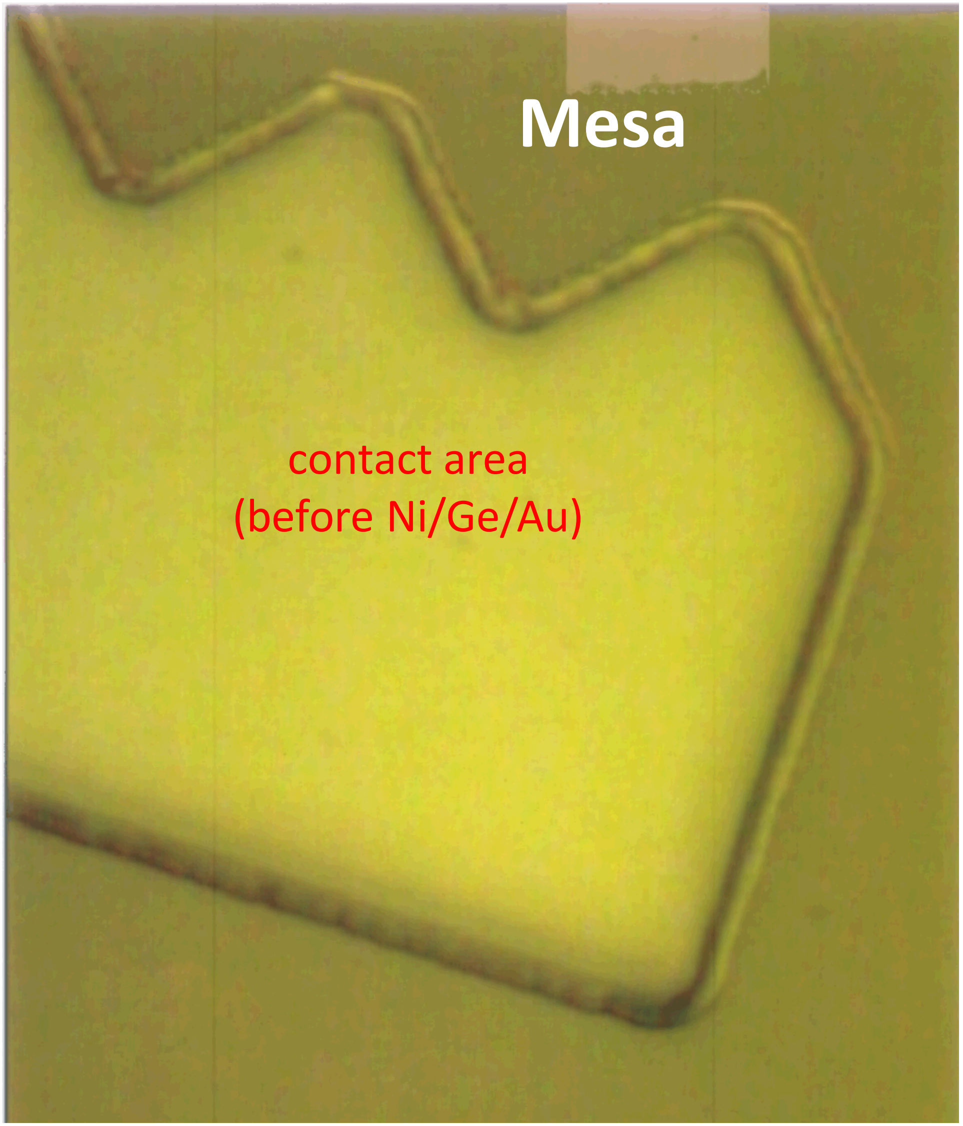
HIGFET

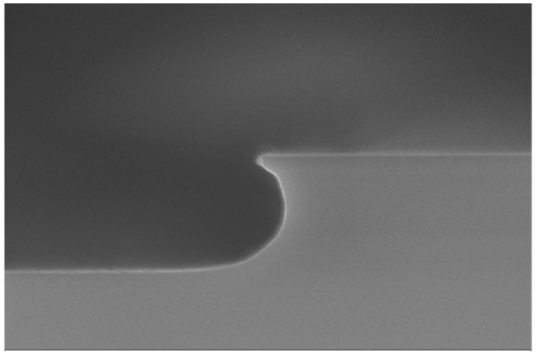


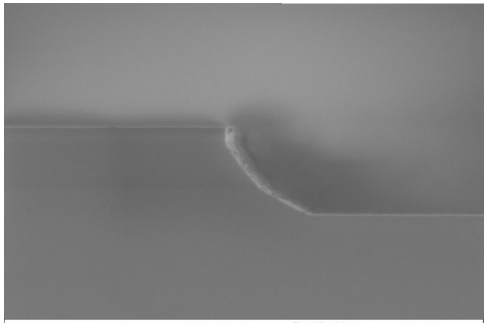


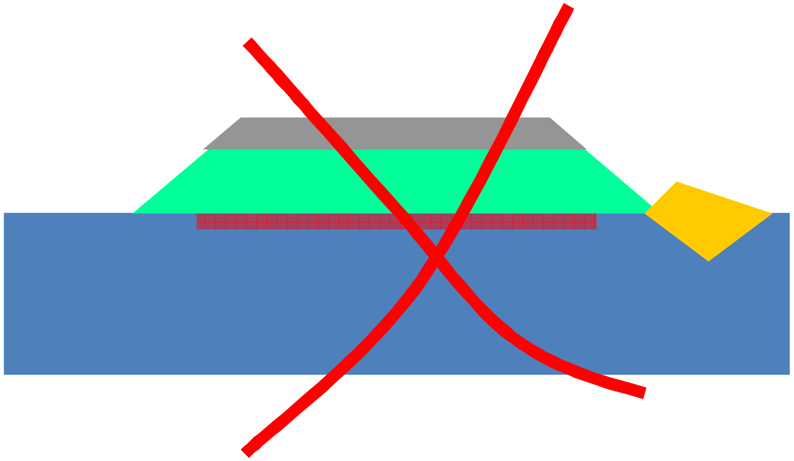
Kane, Pfeiffer, West, and Harnett, APL,1993

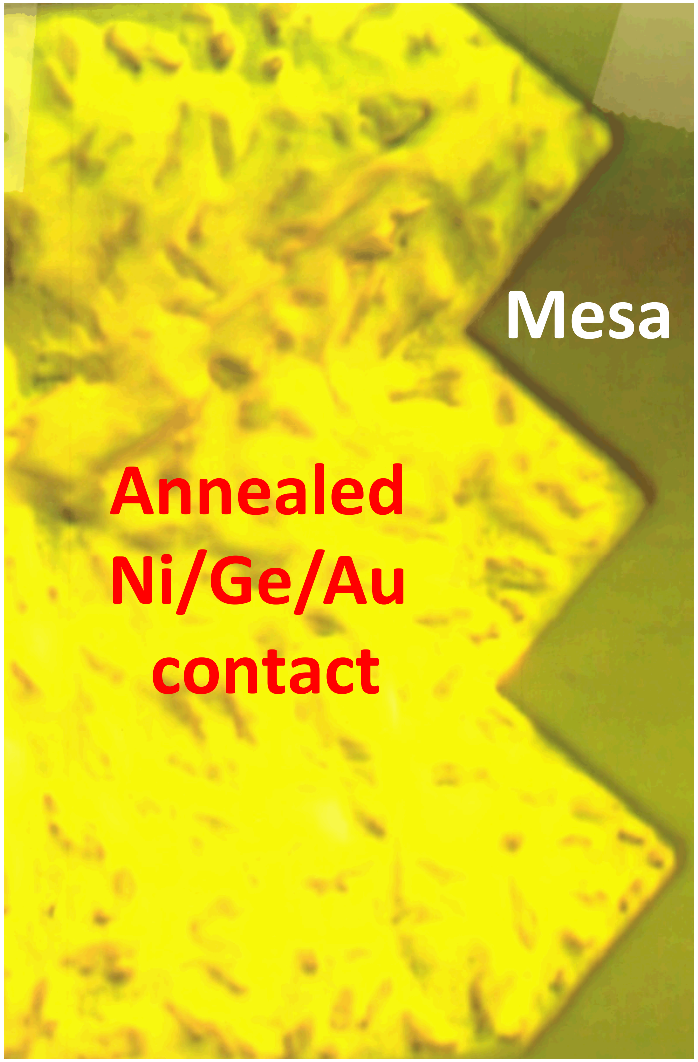
Straight sidewall is important

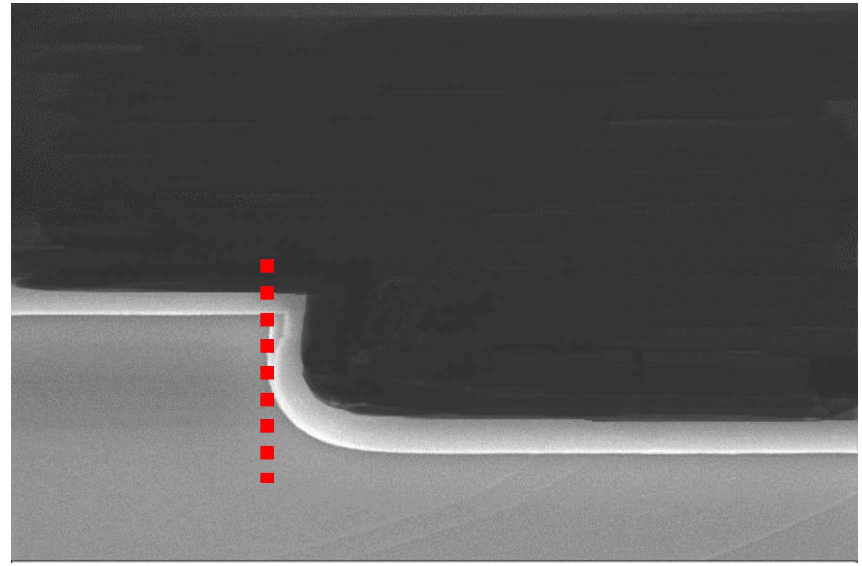






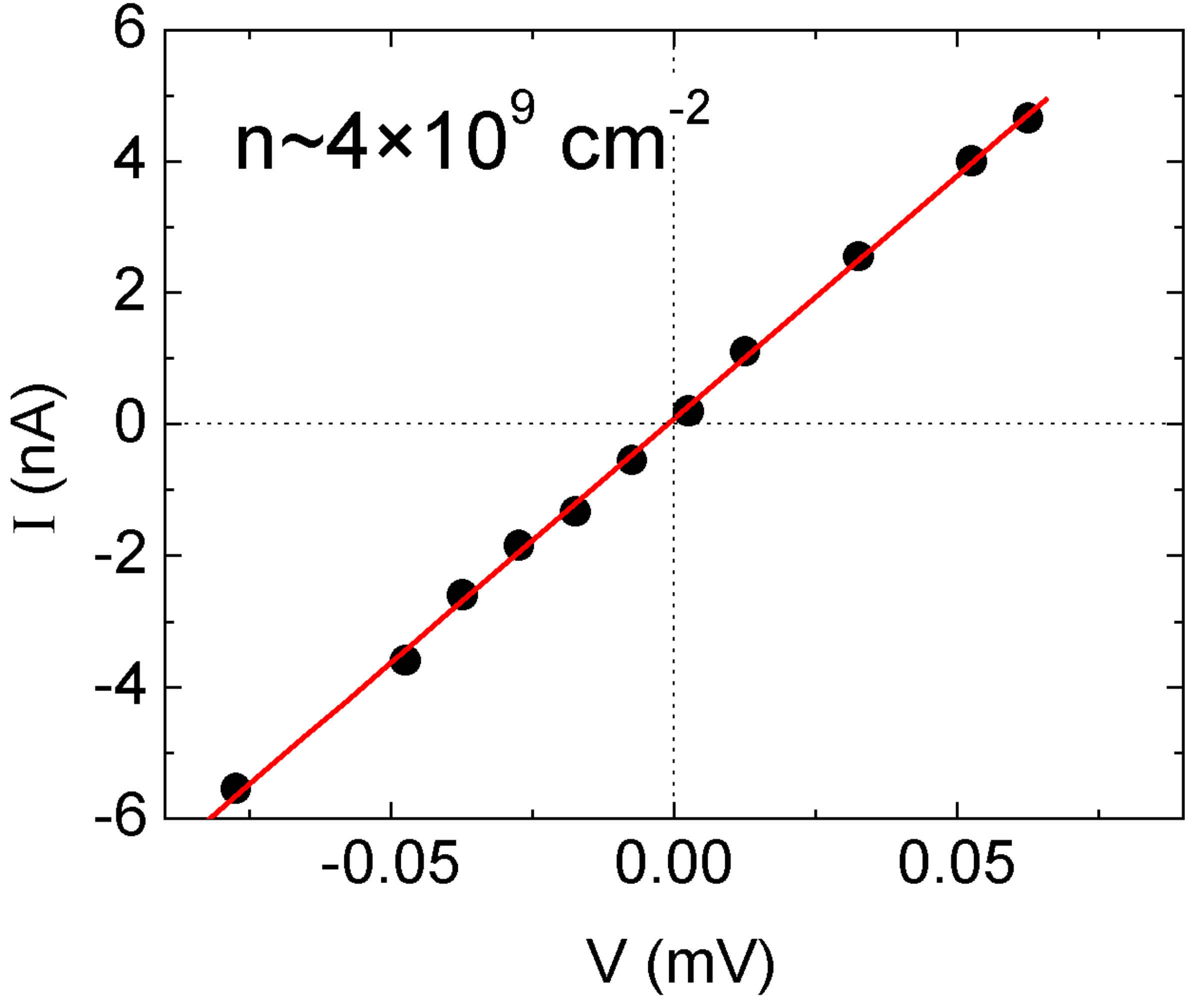




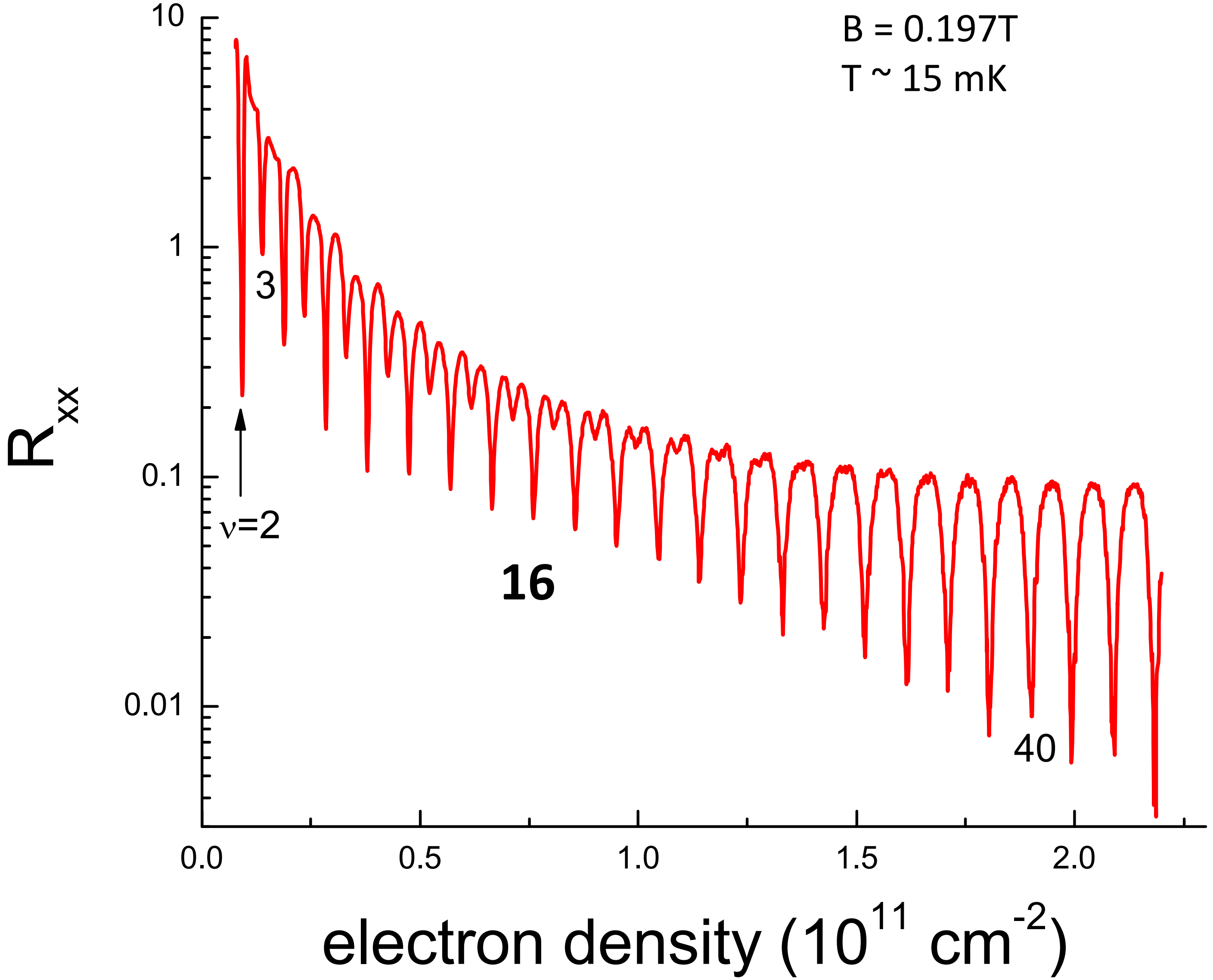


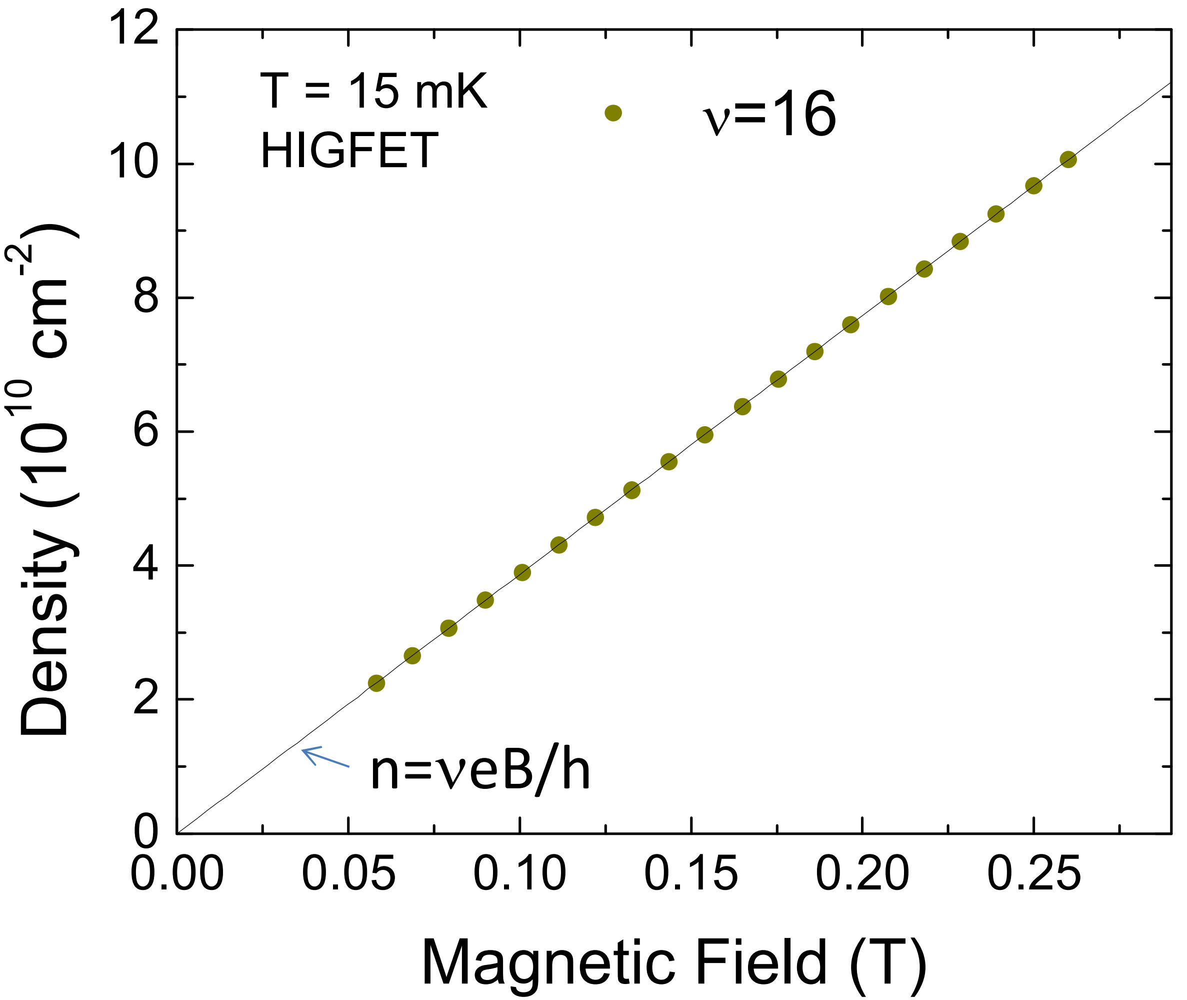
device works!

Linear I-V at very low densities

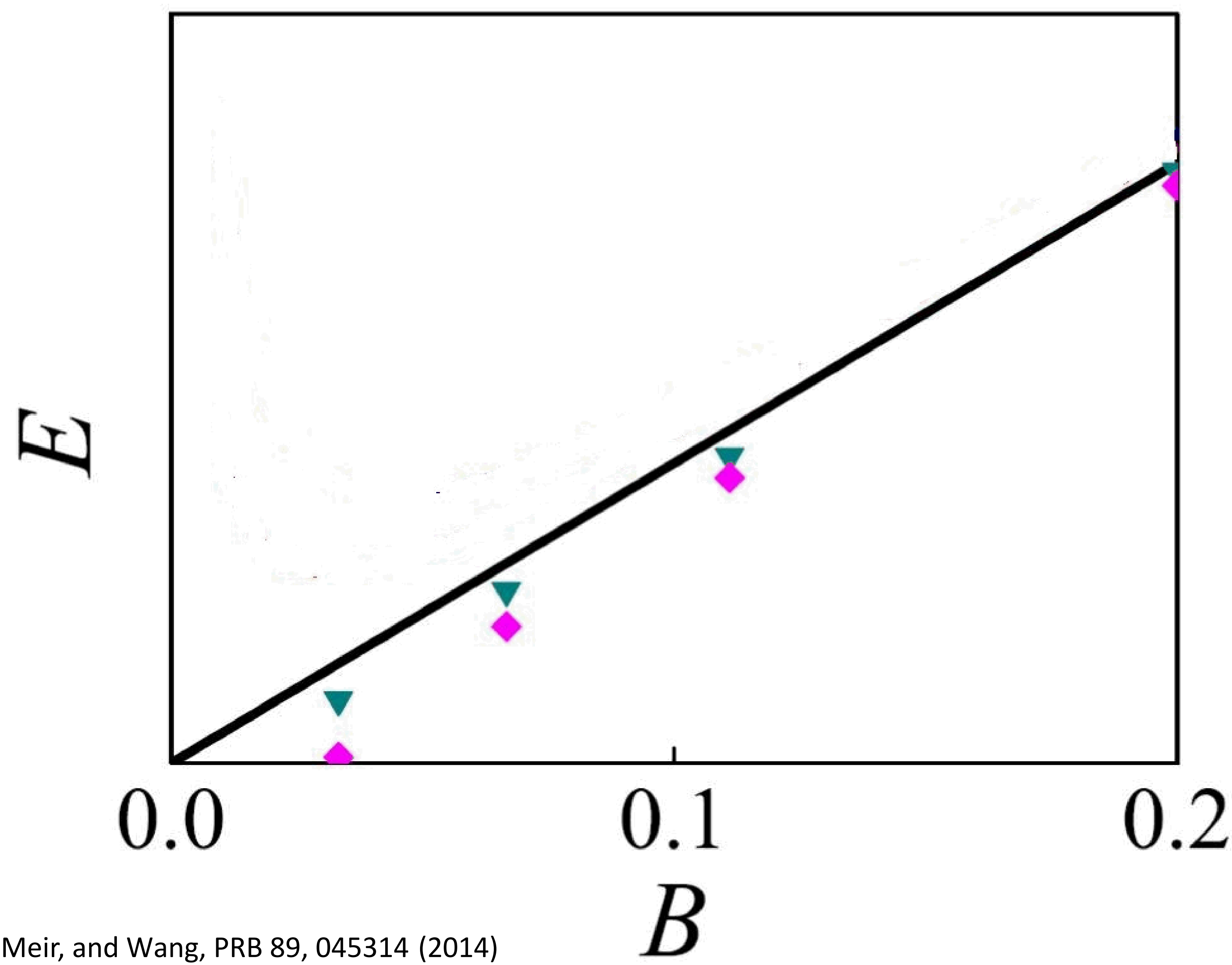


SdH oscillations at B ~ 0.2T



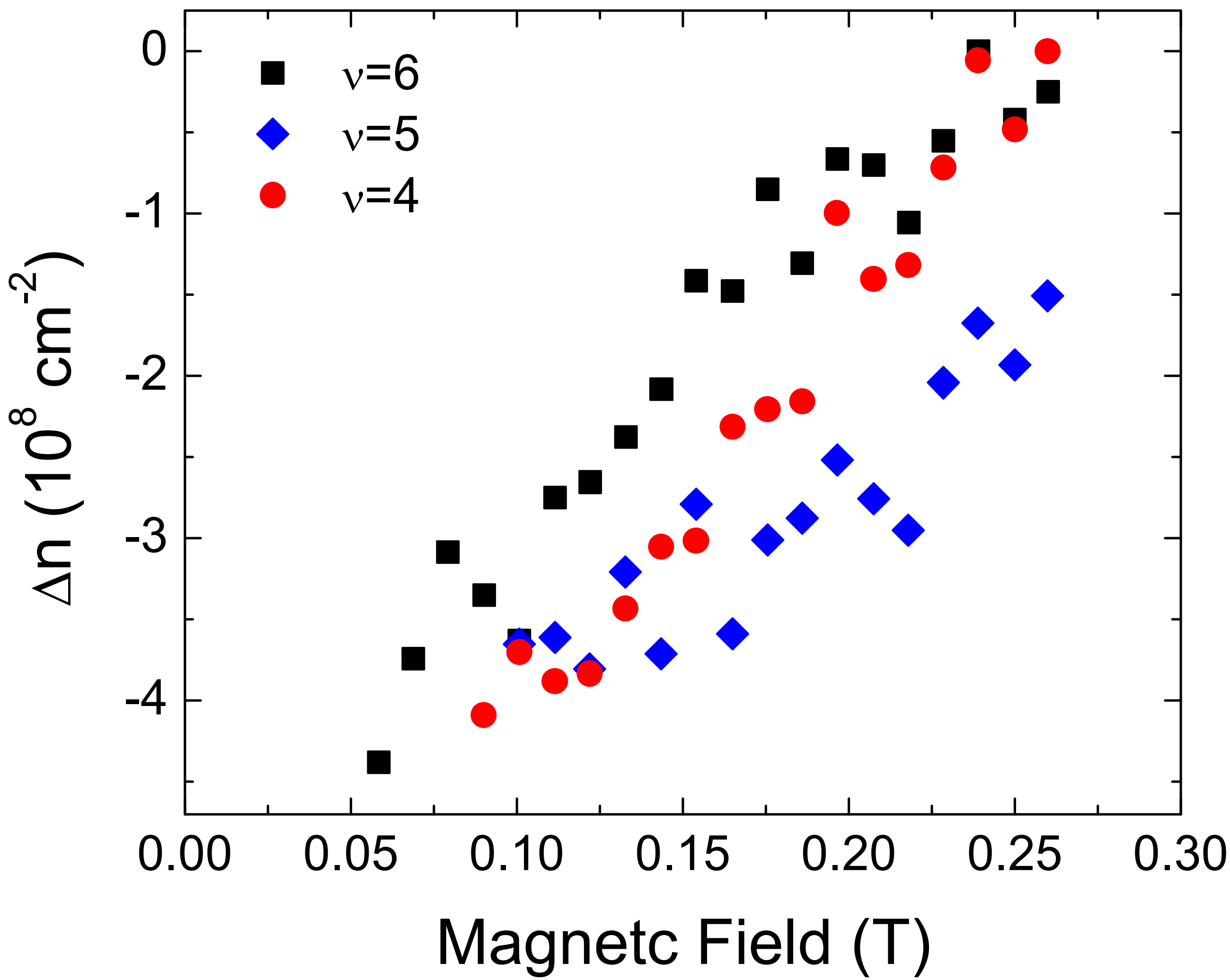

T = 15 mK
HIGFET
ν=16
n=νeB/h
Density (10^{10} cm^{-2})
Magnetic Field (T)
0
2
4
6
8
10
12
0.00
0.05
0.10
0.15
0.20
0.25

Floating or anti-floating of Landau levels in vanishing B field?

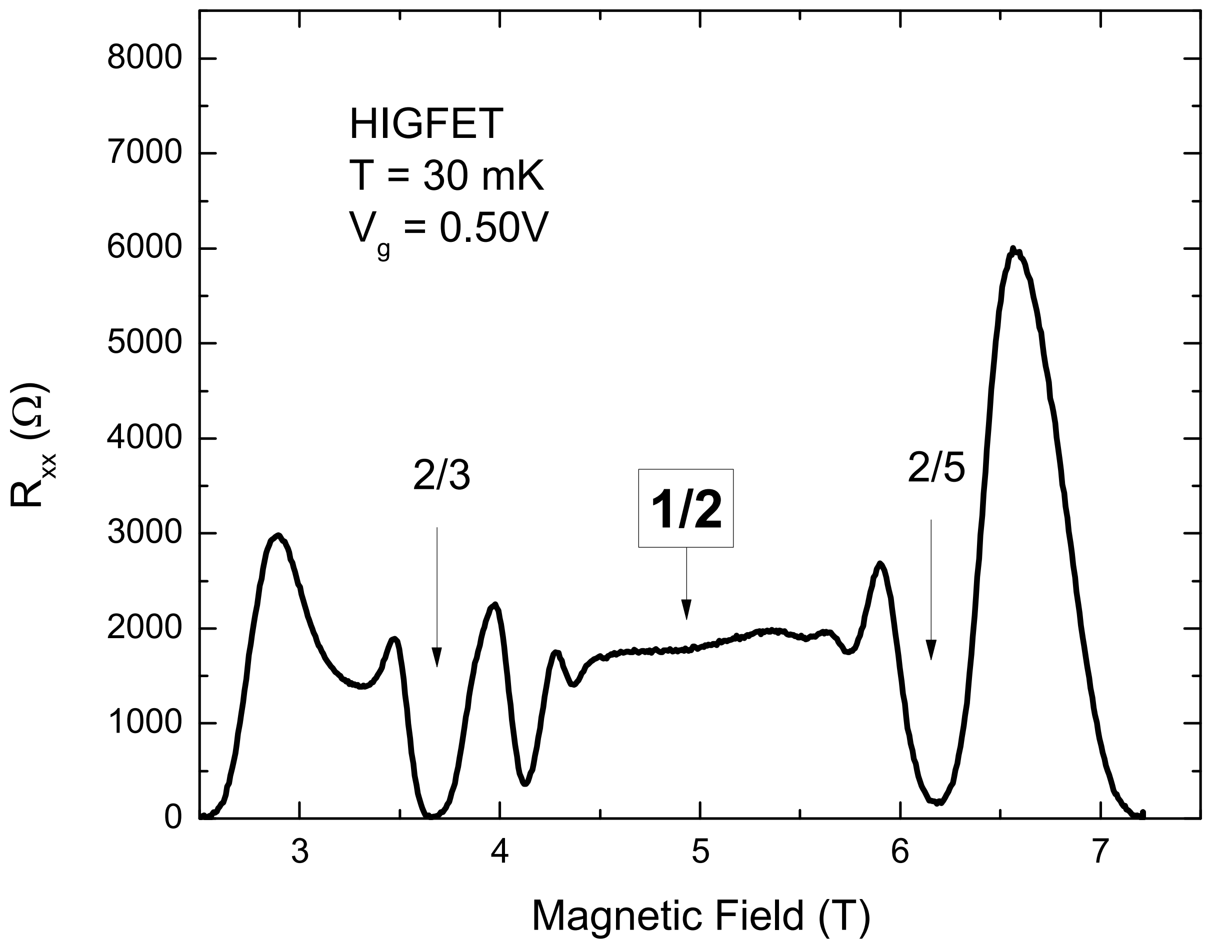


Wang, Avishai, Meir, and Wang, PRB 89, 045314 (2014)

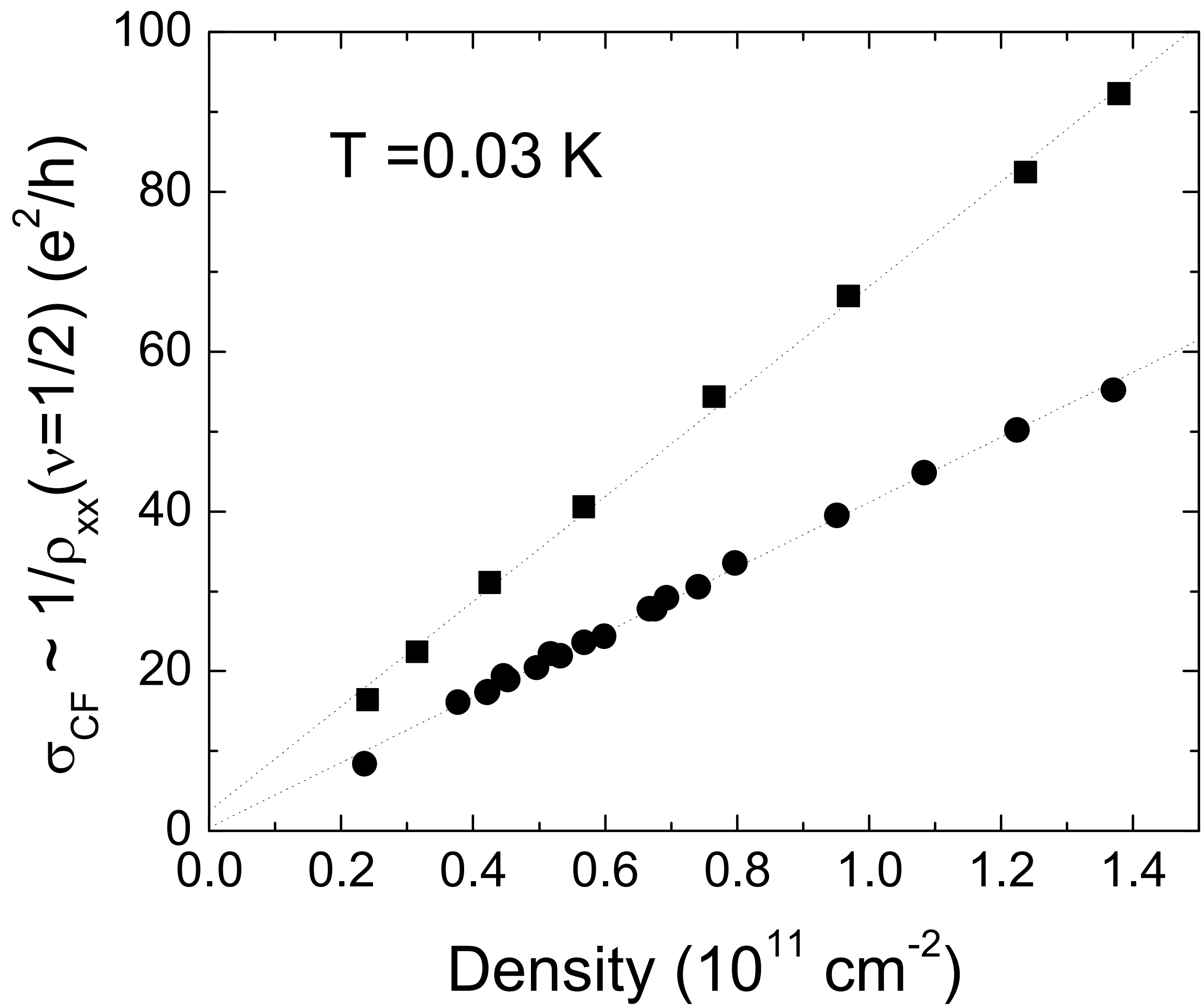
Observation of anti-floating in vanishing B field



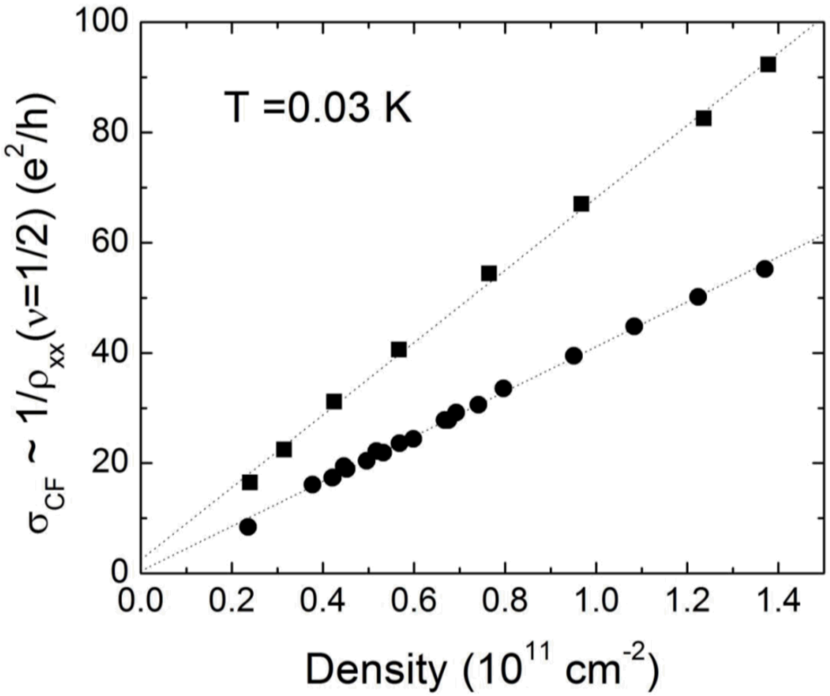
Composite fermions in HIGFET



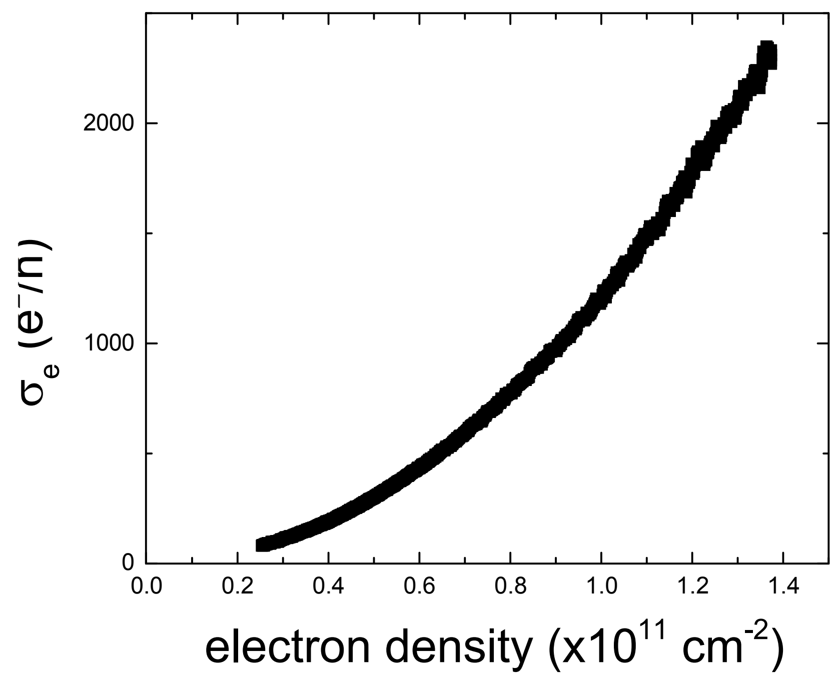
CF conductivity *versus* density

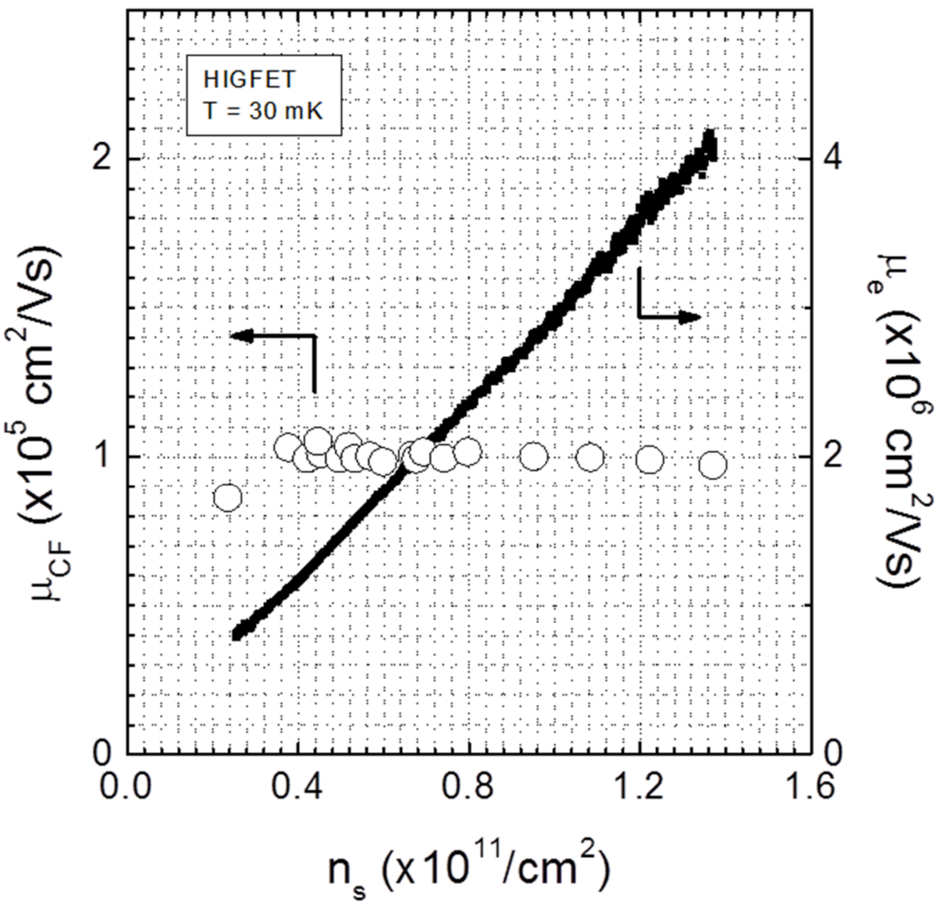


CF conductivity



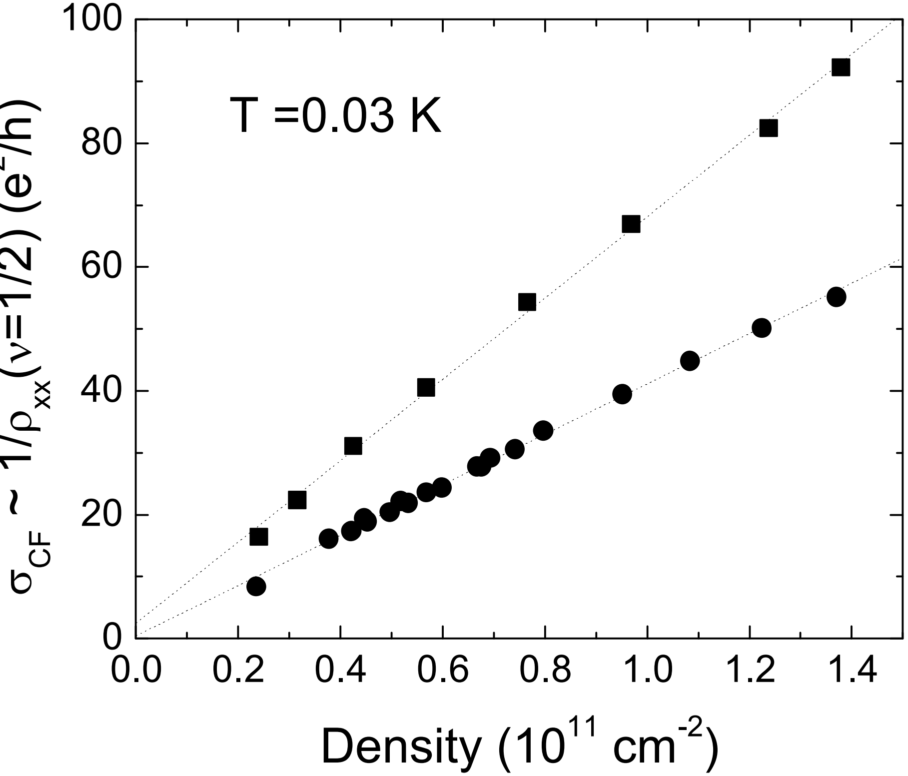
Electron conductivity

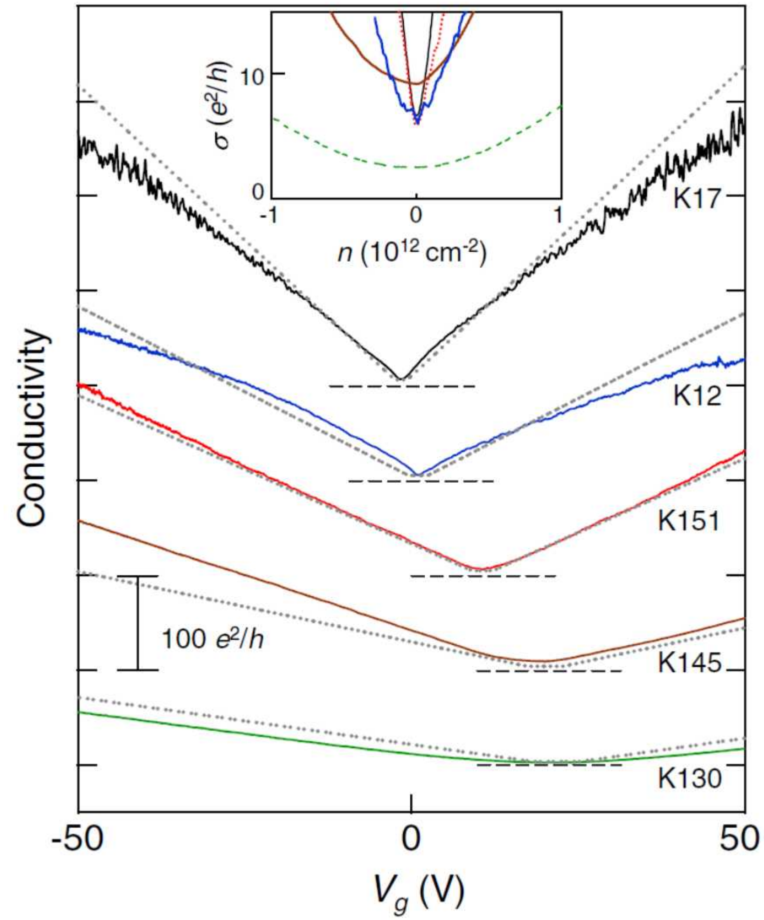




HIGFET
T = 30 mK
μ_{CF} (x10^5 cm^2/Vs)
μ_e (x10^6 cm^2/Vs)
n_s (x10^{11}/cm^2)
0
1
2
0
2
4
0.0
0.4
0.8
1.2
1.6

Linear dependence in graphene

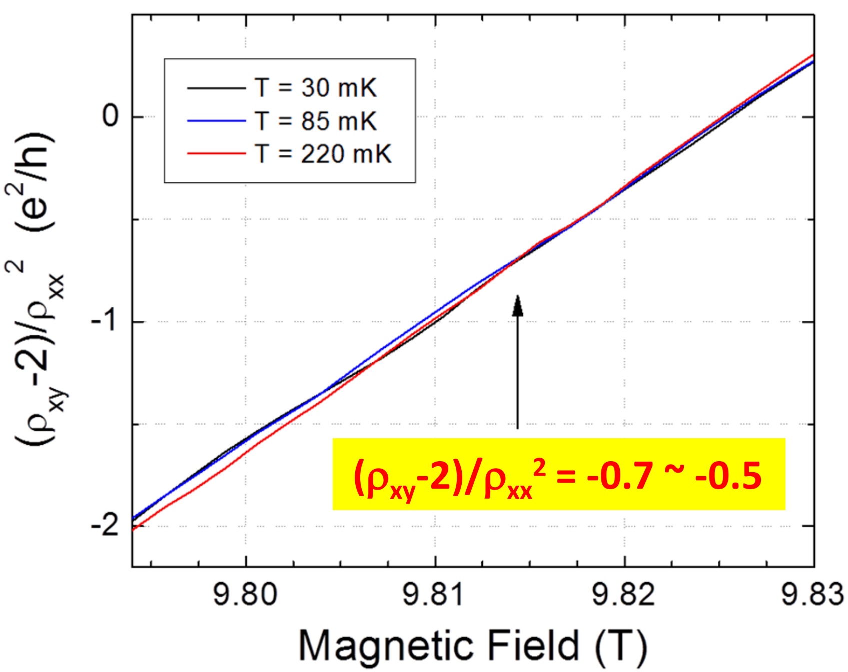


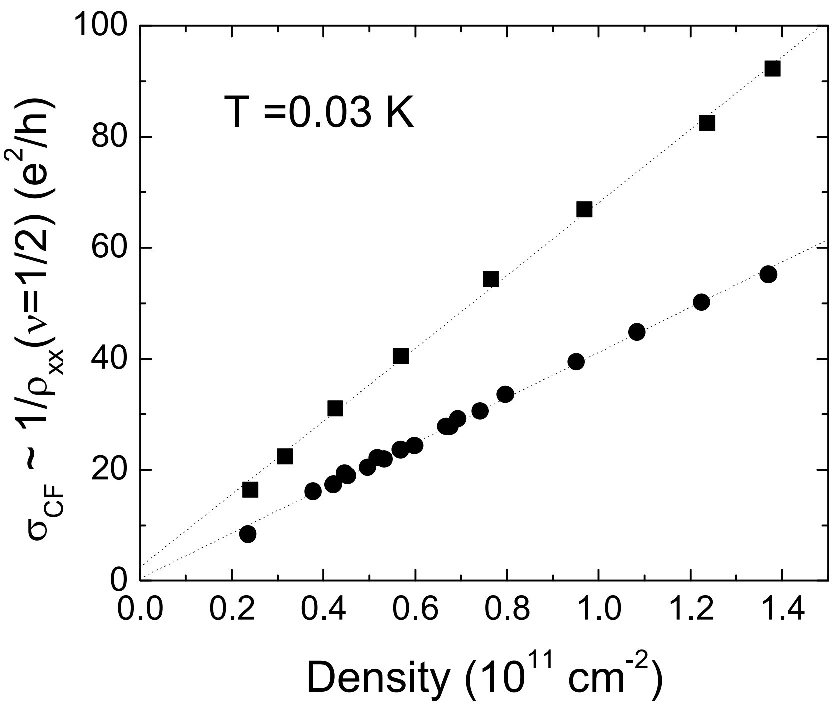


Tan *et al.* PRL (2007).

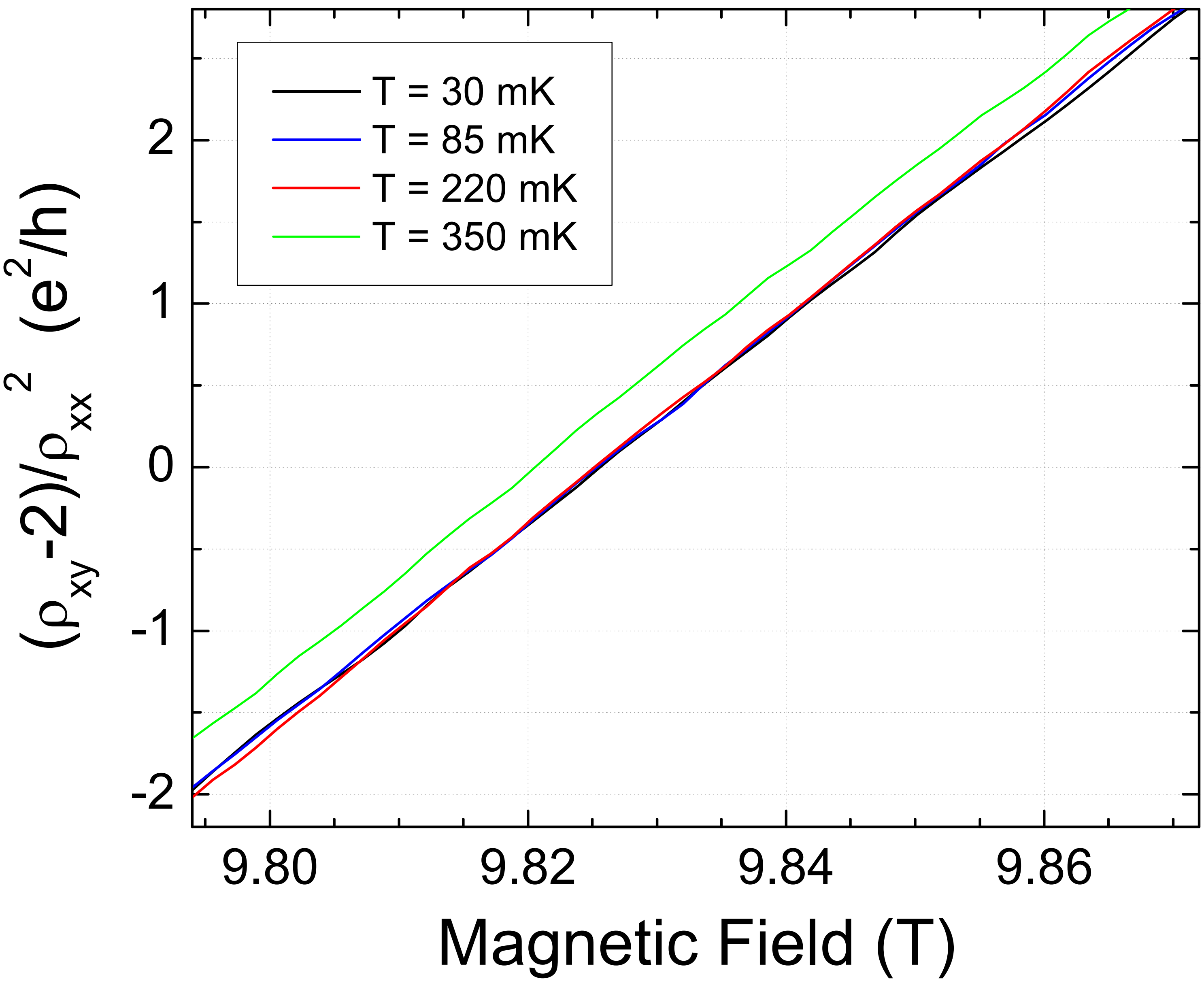
CFs are Dirac fermions

- Resistivity scaling
- Linear density dependence of conductivity



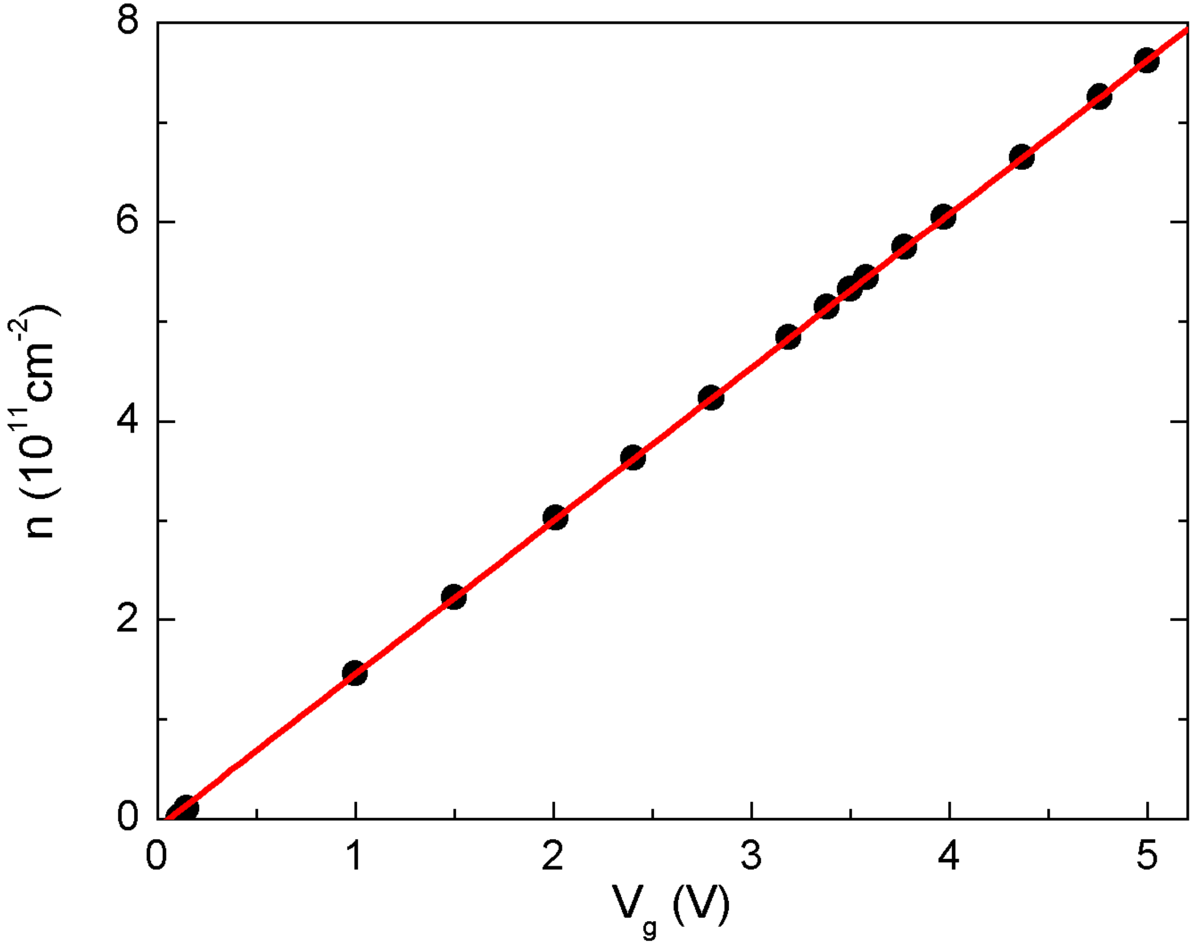


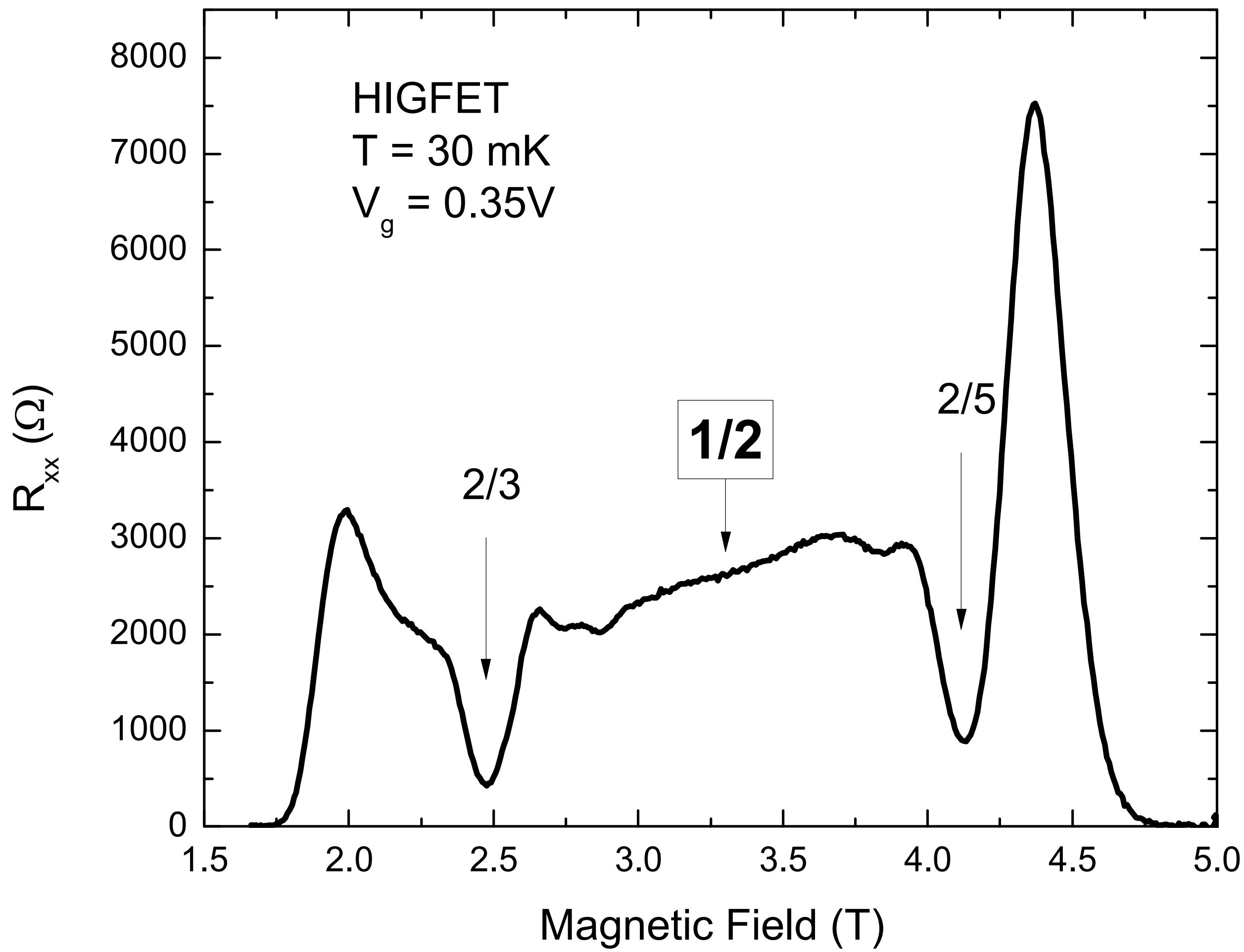
Thank you


T = 30 mK
T = 85 mK
T = 220 mK
T = 350 mK
2
1
0
-1
-2
9.80
9.82
9.84
9.86
$(\rho_{xy}-2)/\rho_{xx}^2$ (e^2/h)
Magnetic Field (T)

Very big density tunable range

~ 1×10^9 to ~ 7.5×10^{11} cm^{-2}





HIGFET
T = 30 mK
V_g = 0.35V
2/3
1/2
2/5
R_{xx} (Ω)
Magnetic Field (T)
0
1000
2000
3000
4000
5000
6000
7000
8000
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0