KOREA UNIVERSITY
Department of Chemical and Biological Engineering

Record-quality two-dimensional electron systems in GaAs/AlAs quantum wells

Yoon Jang Chung

12th School of Mesoscopic Physics, May 2023

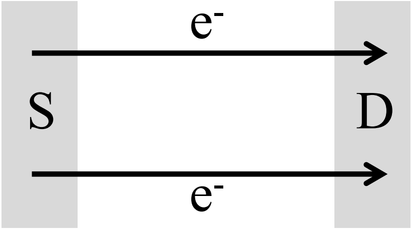
Outline

- Introduction
    - Clean 2DESs and the GaAs/AlAs materials group
- 2DESs in GaAs/AlAs quantum wells
    - Defining GaAs and AlAs 2DESs
    - Systematic impurity reduction
    - Record-quality AlAs and GaAs 2DESs
- Summary

Clean 2DESs

$\mu_{tr} \sim 10^7$ cm^2/Vs

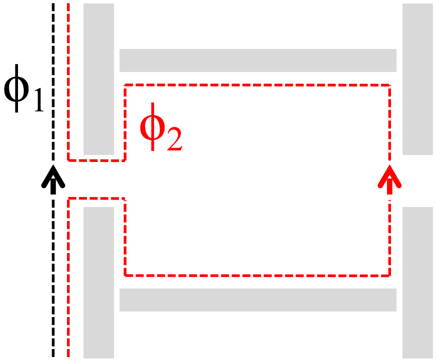
Mean free path ~ 100 μm



Ballistic transport

$\mu_q \sim 10^6$ cm^2/Vs

Coherence length ~ 10 μm



Quantum interferometry

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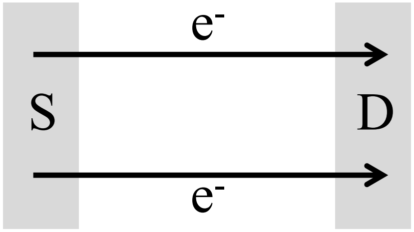

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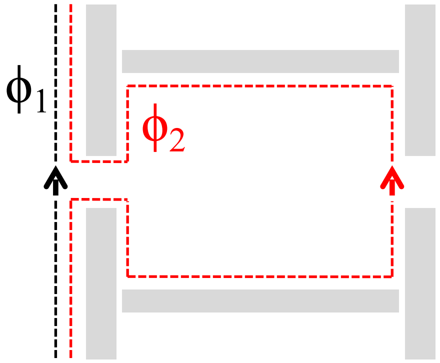
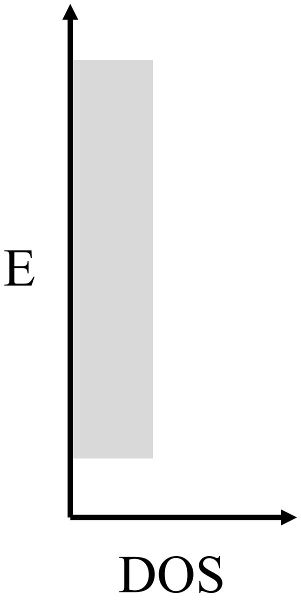


Quantum interferometry



$$E_{Coul} = \frac{e^2}{4\pi\epsilon r} = \frac{e^2\sqrt{n}}{4\pi\epsilon}$$

$$E_{Fermi} = \frac{\pi\hbar^2 n}{m^*}$$

Many-body physics

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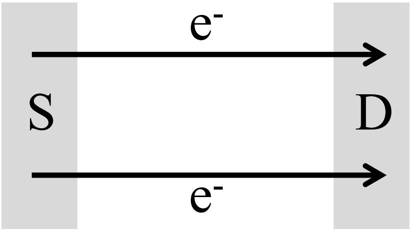

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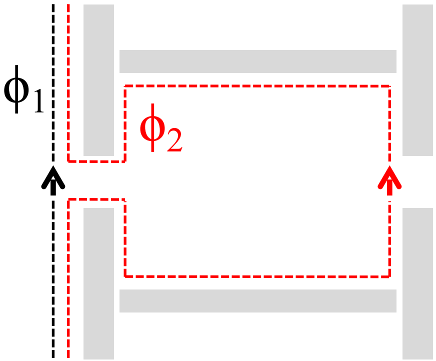

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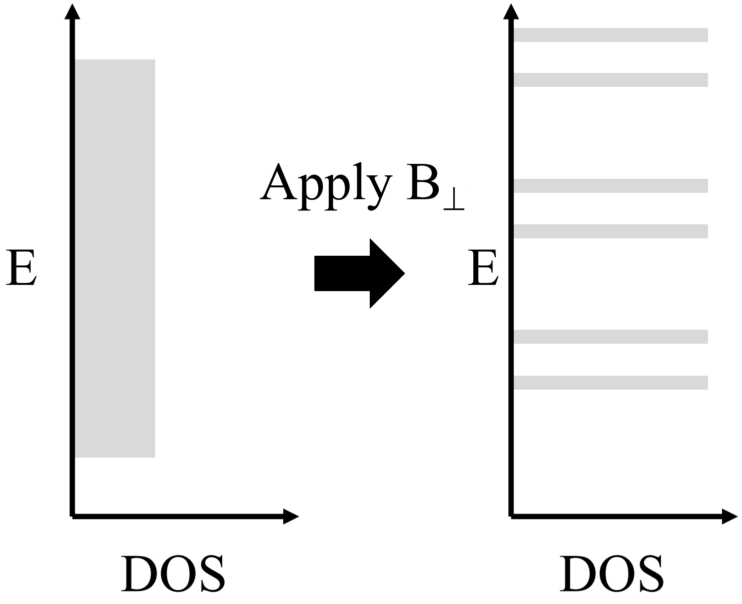

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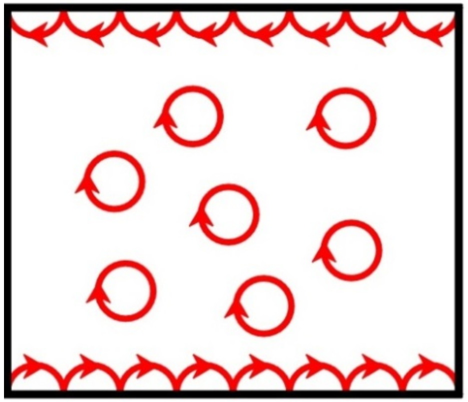
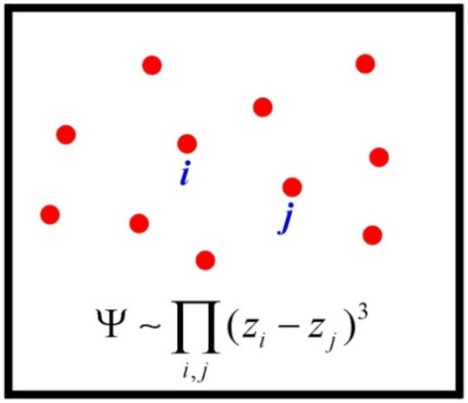
Many-body physics

Physics of clean 2DESs under a magnetic field



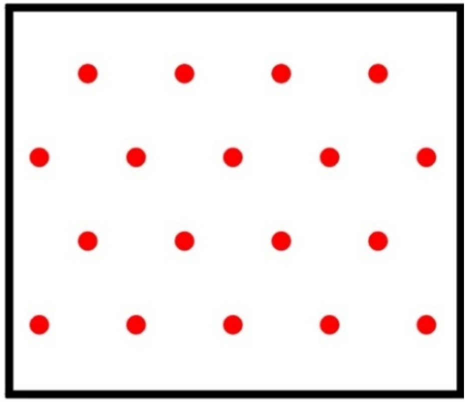
$\nu = 1$

Integer QHE



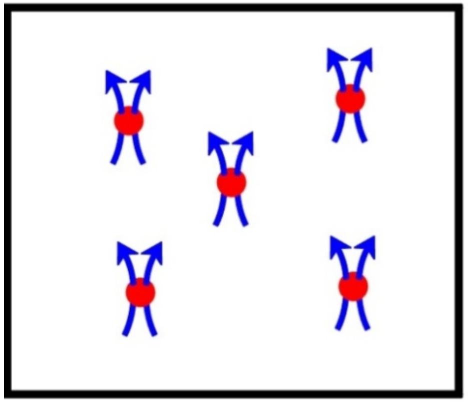
$\nu = 1/3$

Fractional QHE



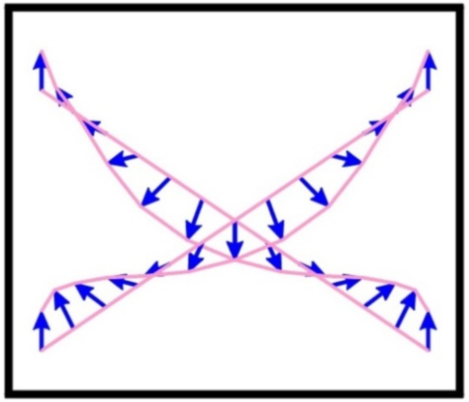
near $\nu = 1/5$

Wigner Crystal



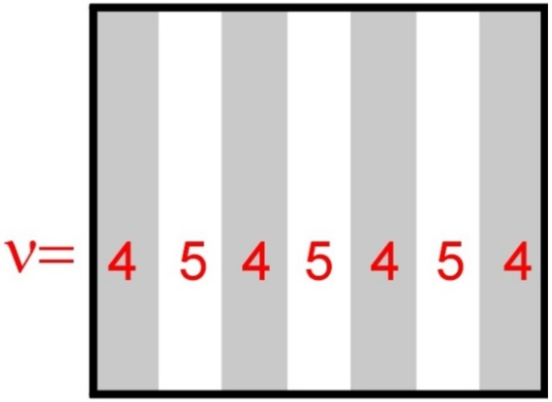
$\nu = 1/2$

Composite Fermions



near $\nu = 1$

Skyrmions



$\nu = 9/2$

Striped Phases

ν = number of occupied Landau levels

Shayegan, arXiv (2005)

Quality and mobility

- ‘Mobility’ is defined as the term that relates applied electric field (driving force) to the drift velocity of electrons ➡ $v_D = \mu E$

- This is a useful quantity to evaluate the ‘quality’ of a material because based on a simple Drude model, it can be related to how long an electron can travel before experiencing a scattering event

Define time interval *t =n dt*

Define τ as the average time between scattering events (then 1/τ is the scattering rate)

Assume applied external force f(t)

Then the equations of motion for electrons in the material are :

$$p(t+dt) = p(t) - p(t)\frac{dt}{\tau} + f(t)dt(1-\frac{dt}{\tau})$$

Momentum at time t+dt

Momentum loss from scattering

Momentum gain from applied external force

Quality and mobility

- Assuming that dt is infinitesimally small so that (1-dt/τ)≈1 and rearranging gives

$$p(t+dt) - p(t) = -p(t)\frac{dt}{\tau} + f(t)dt \quad \Rightarrow \quad \frac{dp}{dt} = -\frac{p(t)}{\tau} + f(t)$$

Divide both sides by dt

- For steady-state DC conductivity, applied force is f=-eE and dp/dt = 0

Then $\frac{p}{\tau} = -eE$

Using $v = \frac{p}{m^*}$

$$v = -\frac{eE\tau}{m^*} \quad \xleftrightarrow{\text{Recall}} \quad v_D = \mu E$$

$$\boxed{\mu = \frac{e\tau}{m^*}}$$

Mobility of the material is related to the mass and scattering time of the material

Quality and mobility

- So how do you measure mobility in real life?

$$j = \sigma E = -nev$$

Current density

Conductivity

Electron density in material

$$\boxed{\sigma = \frac{j}{E} = -\frac{nev}{E} = -ne\mu = \frac{1}{\rho}}$$

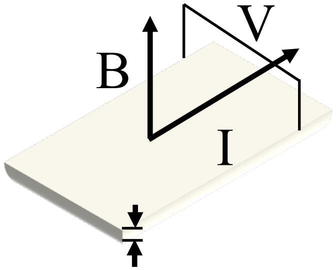
- Measure resistivity with I-V ↔
- Measure electron density with Hall effect

Resistivity (Geometry independent)

$$R = \rho\frac{L}{A} = \frac{V}{I}$$

Input/Output

Resistance of sample (Depends on geometry of sample)



Sample thickness t

$$R_H = -\frac{1}{ne} = \frac{E}{jB}$$

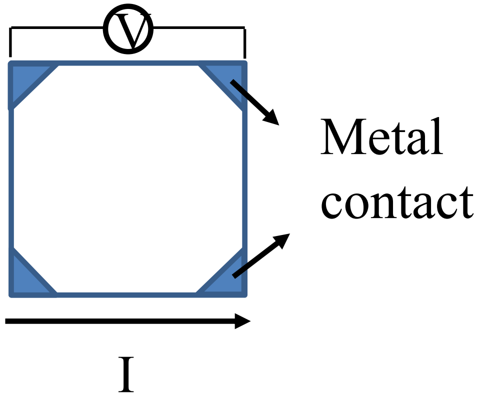
$$= \frac{Vt}{IB}$$

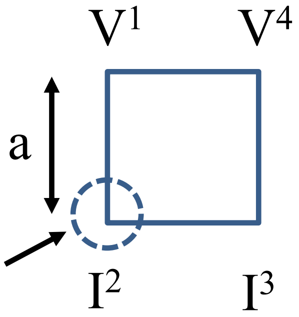
Input/Output

Quality and mobility

Use four-point method to minimize influence of contact resistance

Assume sample is a true square, correct equations for current spread and modify to be compatible with 2D





Injected current spreads in a circular symmetric pattern

$$E = \rho j$$

$$j = 4 \times \frac{I}{2\pi r}$$

Current can only flow in one of the 4 quadrants

$$V^4 - V^1 = \rho \int_1^4 \frac{2I}{\pi r} dr$$

$$= \rho \frac{2I}{\pi} ln\sqrt{2} = I\rho \frac{ln2}{\pi}$$

$$\frac{V}{I} = R = \rho \frac{ln2}{\pi}$$

$$\Rightarrow \boxed{\rho = R \frac{\pi}{ln2}}$$

The GaAs/AlAs materials group

- Commercially available GaAs substrates
- Near-perfect stoichiometry is possible
  - Growth rate determined by Ga/Al flux
- GaAs-AlAs are nearly lattice matched
  - Lattice mismatch < 0.2% at RT

➡ Excellent compatibility with molecular beam epitaxy in UHV

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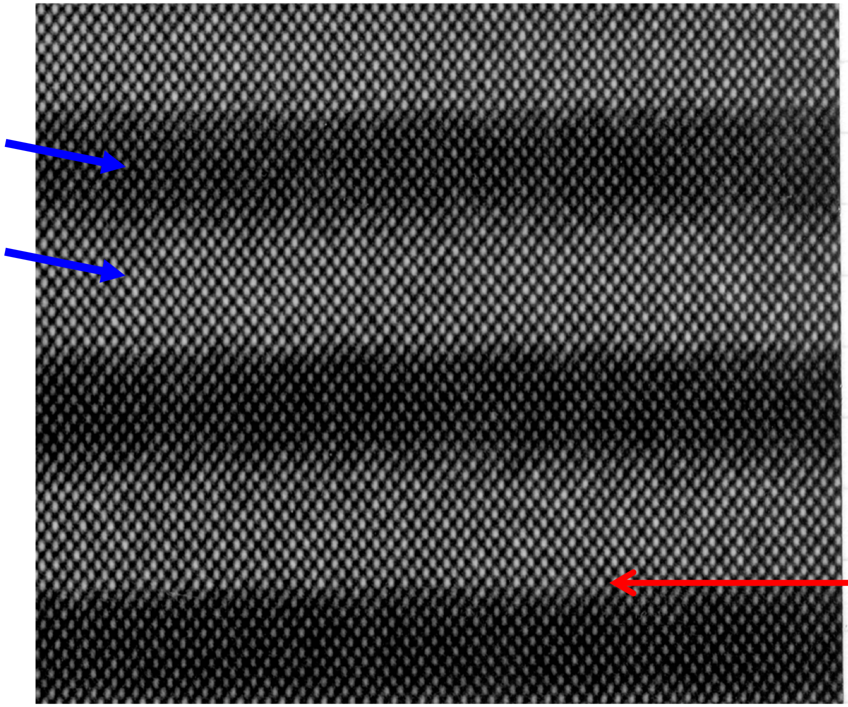

MBE superlattice of 12 layers of GaAs and 12 layers of AlAs

Perfect rows of atoms

No dangling bonds

No interface states

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➡ Excellent compatibility with molecular beam epitaxy in UHV

- Complete miscibility of Al in GaAs
  - Band properties vary continuously
- Significant difference in band gaps
  - Γ band : ~1.5 eV for GaAs, ~3.1 eV for AlAs
  - X band : ~1.9 eV for GaAs, ~2.2 eV for AlAs

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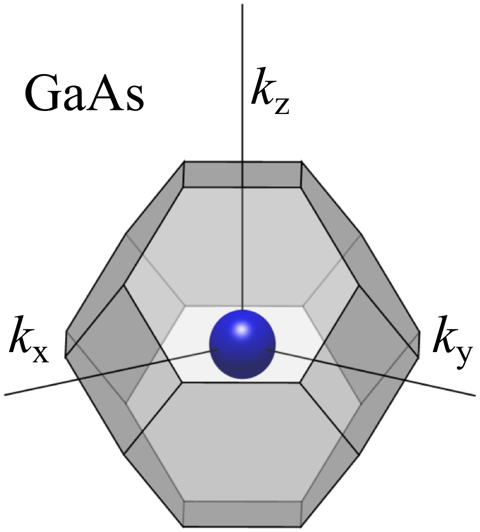
➡ Can define quantum wells that can host 2DESs

Optimal choice for the preparation of clean 2DESs!

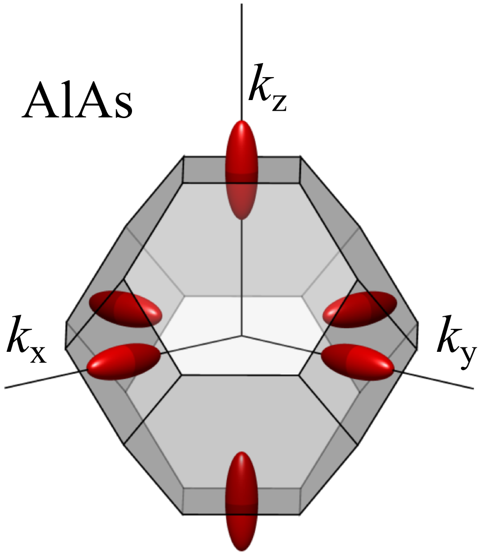
GaAs vs AlAs



Single valley

$m^* = 0.067\ m_e$
(Isotropic)

g = -0.44
$\epsilon = 13$



Multi-valley

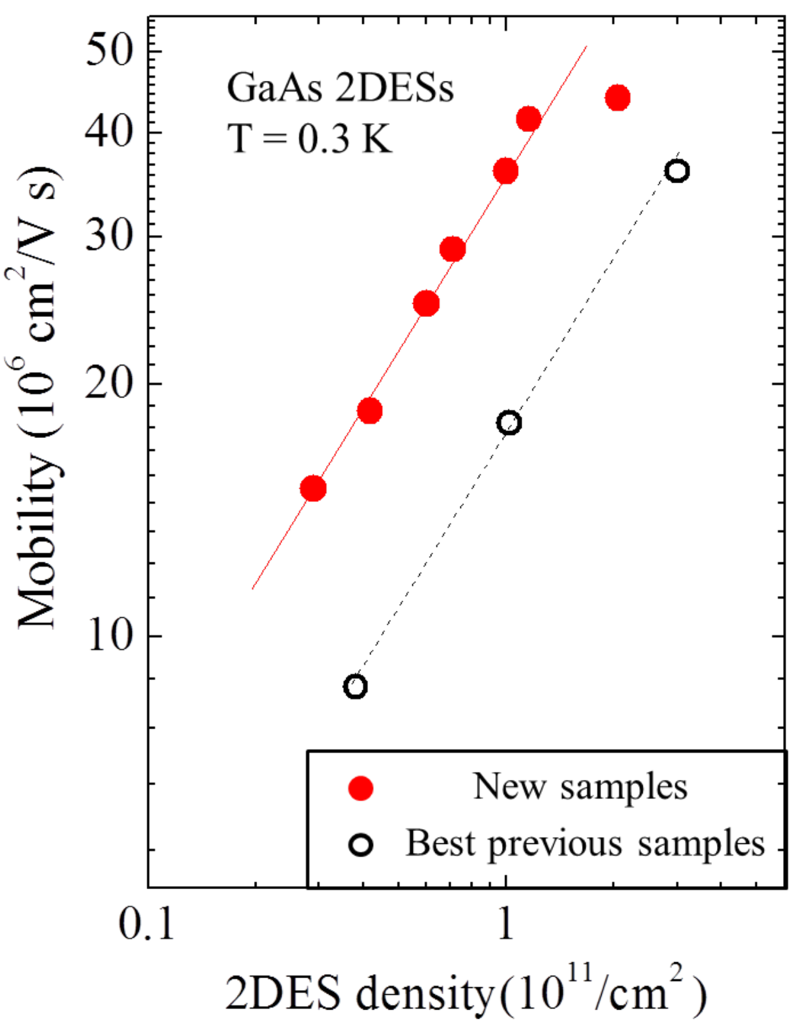
$$\begin{cases} m^*_l = 1.1\ m_e \\ m^*_t = 0.2\ m_e \end{cases}$$
(Anisotropic)

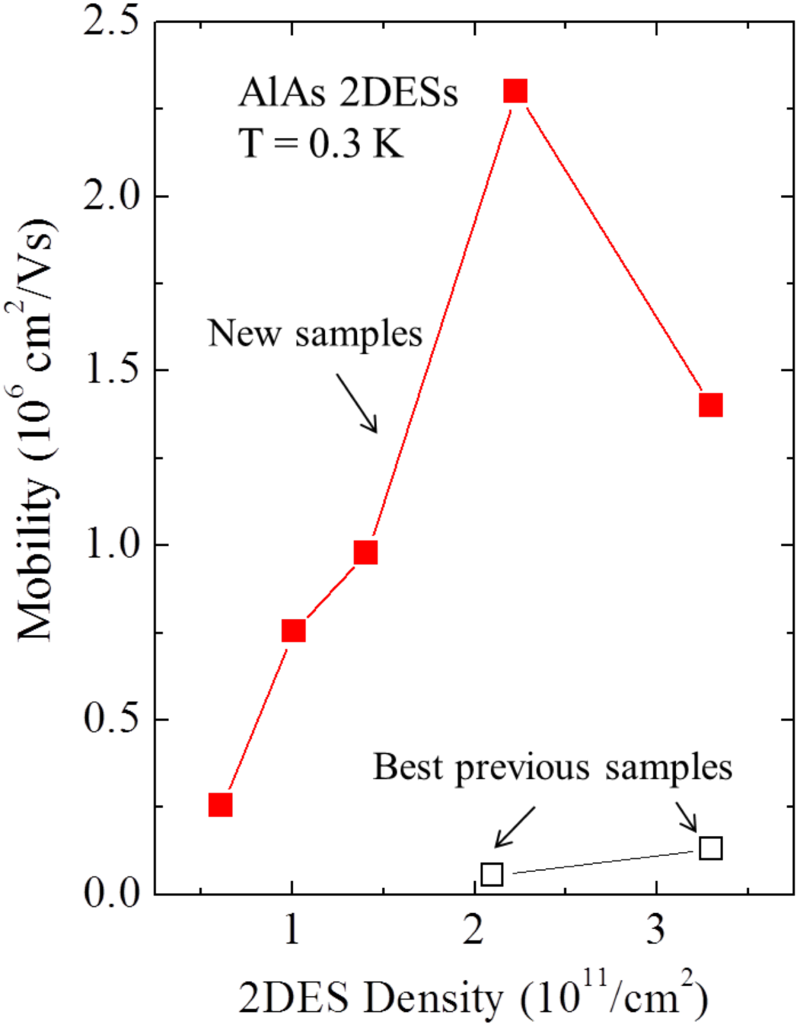
g = 2.0
$\epsilon = 10$

$$E_{Coul} = \frac{e^2}{4\pi\epsilon r} = \frac{e^2\sqrt{n}}{4\pi\epsilon}$$

$$E_{Fermi} = \frac{\pi\hbar^2 n}{m^*}$$

Record-quality GaAs and AlAs 2DESs





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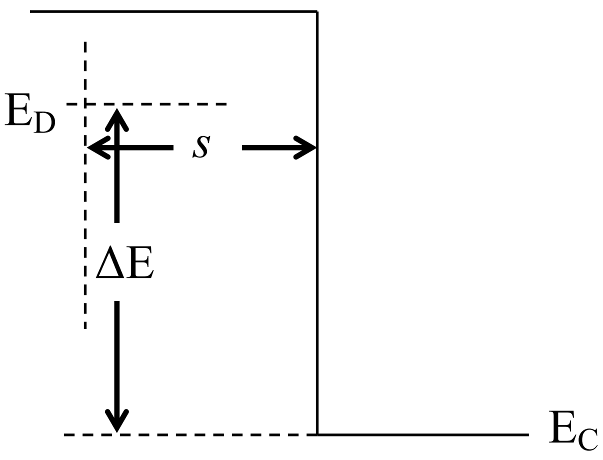
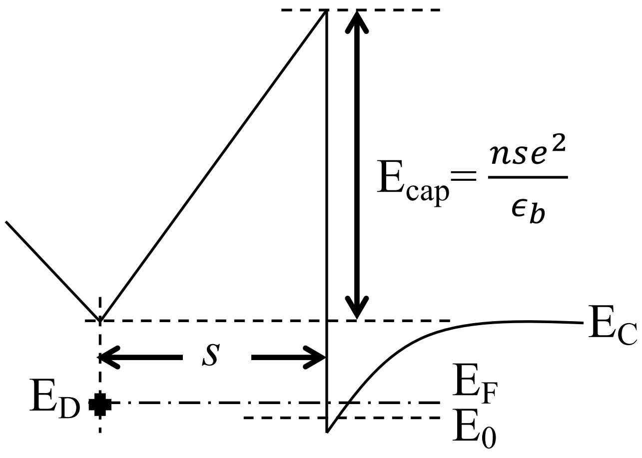
Preparing 2DESs - Modulation doping

Before equilibration

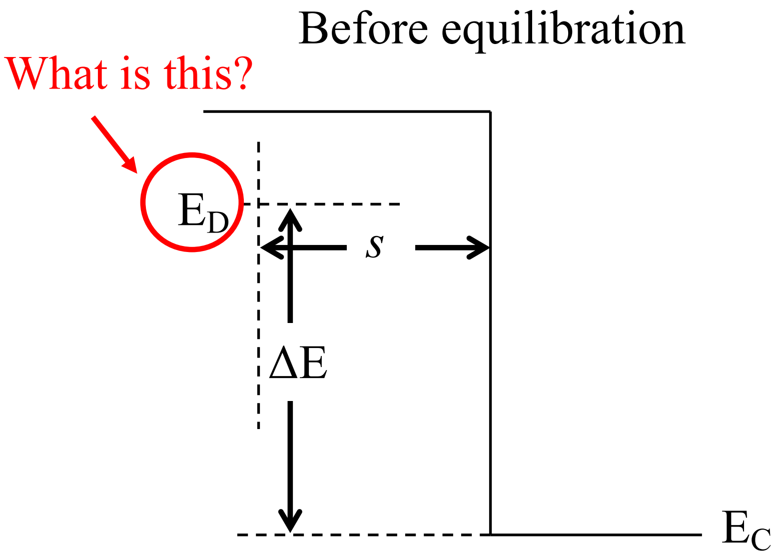


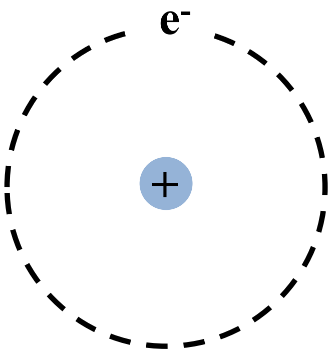
After equilibration



- Concept first introduced by Störmer (Solid State Comm. **29**, 705 (1979))
- Reduce scattering by separating ionized impurity and 2DESs

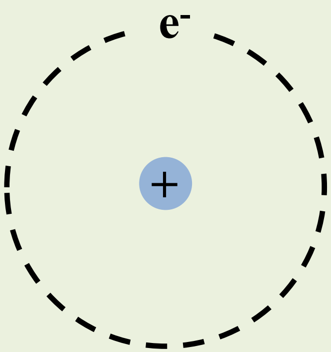
Preparing 2DESs - Modulation doping





Hydrogen atom

Semiconductor bulk



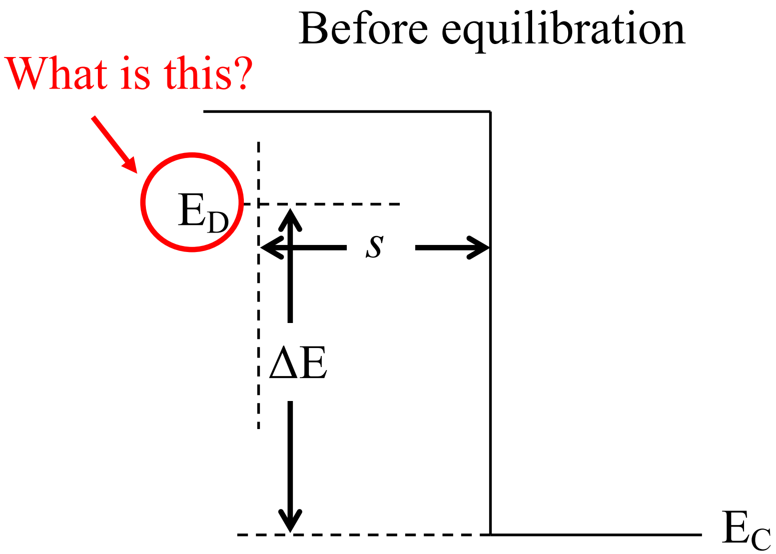
Donor `atom'

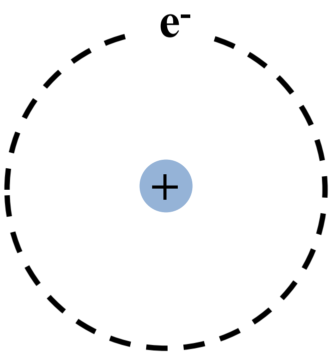
$$E_0 = \frac{me^4}{8\epsilon_0^2 h^2}$$

$$E_D = \frac{m^* e^4}{8(\epsilon_s \epsilon_0)^2 h^2}$$

- In most cases, donor level can be determined by the hydrogenic model
- Assume that dopant acts like a hydrogen atom (1 `proton', 1 electron)

Preparing 2DESs - Modulation doping





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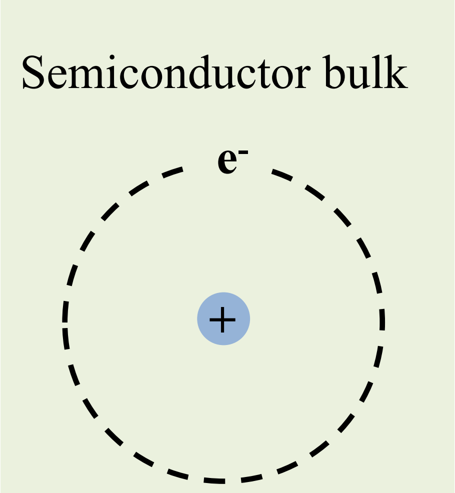

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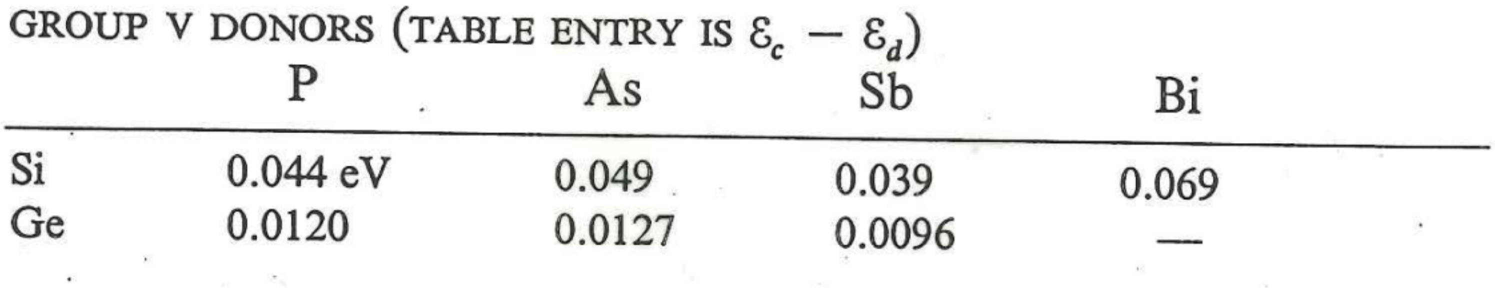
- For example, Si has m_{DOS}^* ~0.4 , ε~12
- Donor atoms should then have roughly 13.6 eV*0.4/144 = 37.6 meV

- Similarly, Ge has m_{DOS}^* ~0.2 , ε~16
- Donor atoms should then have roughly 13.6 eV*0.2/196 = 13.8 meV

Preparing 2DESs - Modulation doping



GROUP V DONORS (TABLE ENTRY IS $\mathcal{E}_c - \mathcal{E}_d$)

	P	As	Sb	Bi
Si	0.044 eV	0.049	0.039	0.069
Ge	0.0120	0.0127	0.0096	—

Table from Ashcroft and Mermin

Preparing 2DESs - Modulation doping

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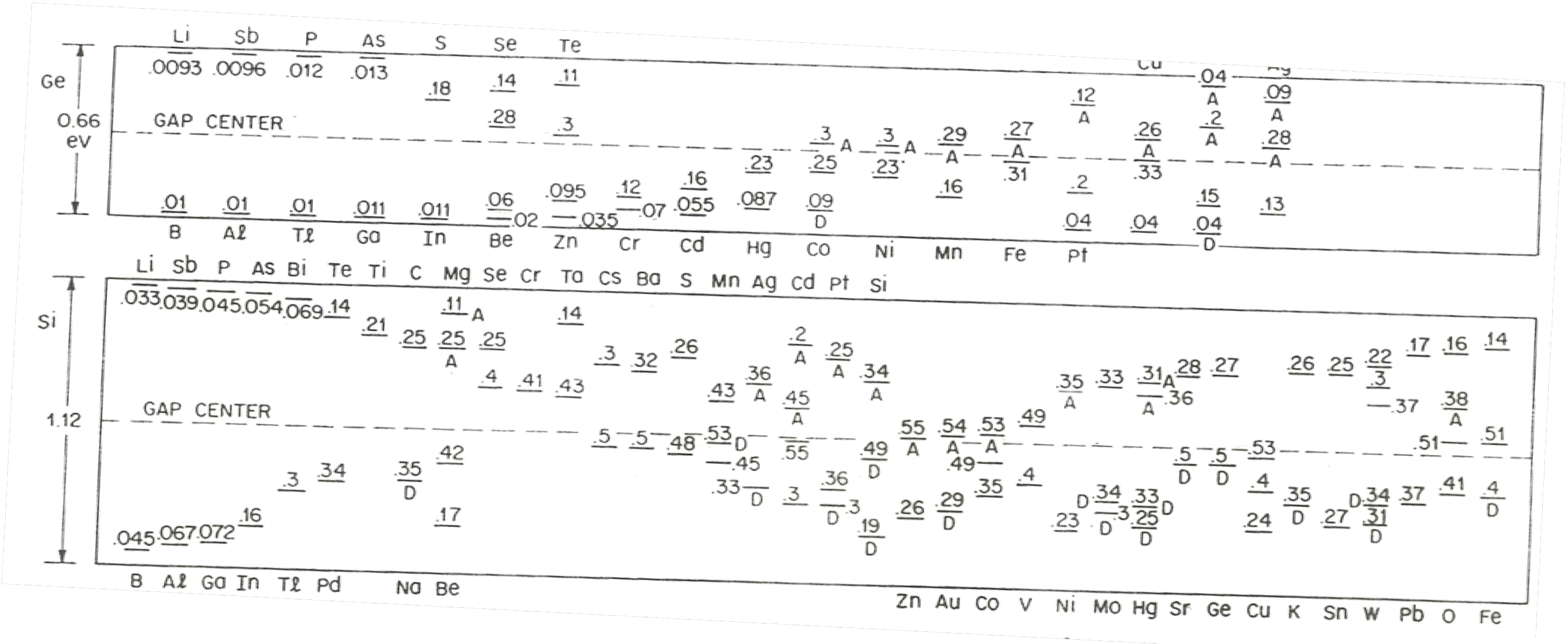


Table from S. M. Sze, Physics of Semiconductor Devices

Preparing 2DESs - Modulation doping

$$\Delta E_C = E_0 + E_F + E_D + \frac{e^2 sn}{\epsilon_0 \epsilon_b}$$

$$n = \frac{1}{s} \frac{\epsilon_o \epsilon_b (\Delta E_C - E_D - E_0 - E_F)}{e^2}$$

$$E_F = \frac{n\pi\hbar^2}{g_v m^*} \quad \text{assume} \quad E_0 = \frac{\pi^2\hbar^2}{2m^* a^2}$$

Some typical numbers :

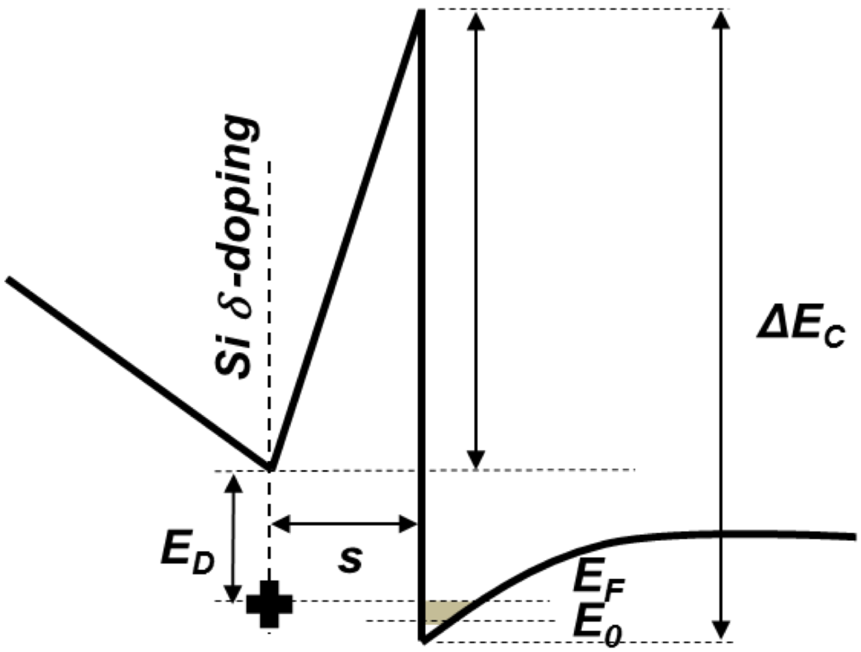
For GaAs QW with

$x = 0.33,\ n = 4.5 \times 10^{11}\ \mathrm{cm}^{-2}$

$$\begin{matrix} E_F = 16\ \mathrm{meV} \\ E_0 = 14\ \mathrm{meV} \end{matrix} \ll \frac{ne^2 s}{\epsilon_0 \epsilon_b} = 240\ \mathrm{meV}$$

$$\therefore \Delta E_C - E_D \simeq \frac{ne^2 s}{\epsilon_0 \epsilon_b}$$

$$n \propto \Delta E_C - E_D$$



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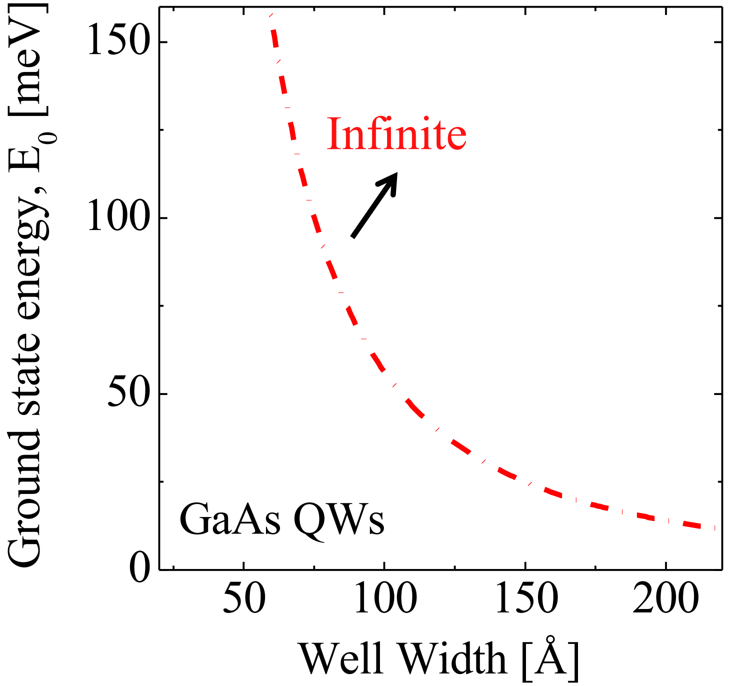

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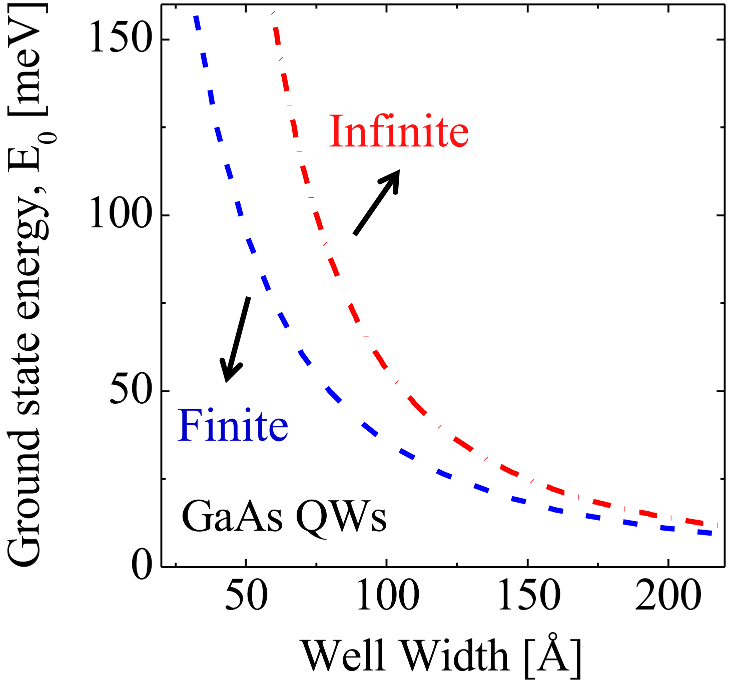

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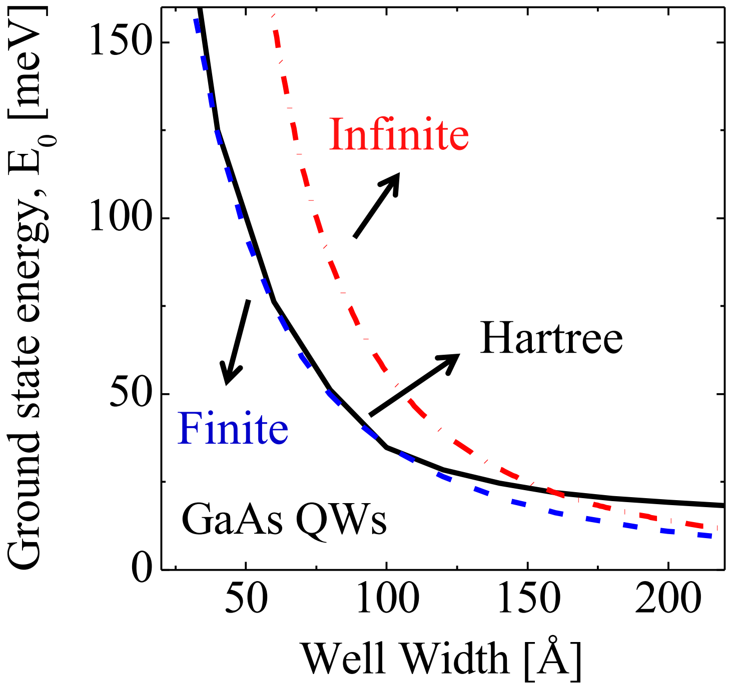

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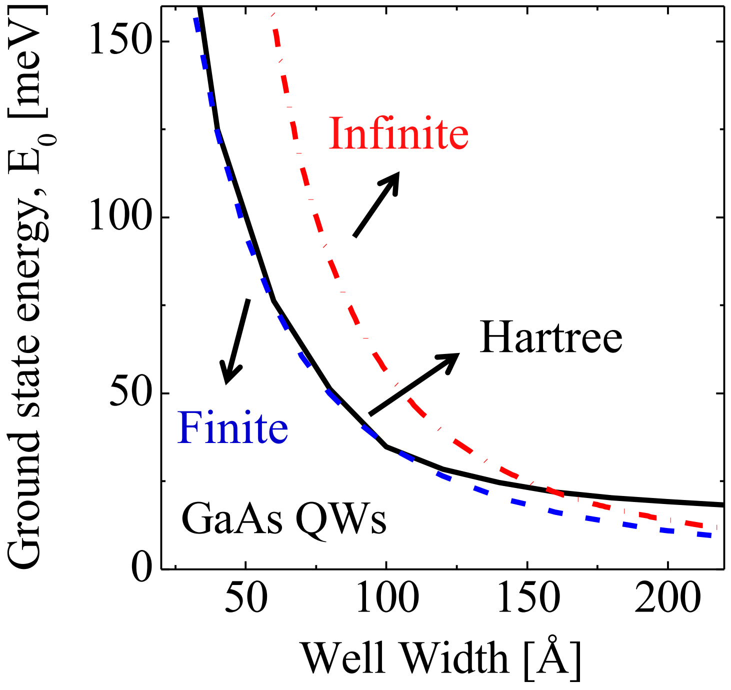
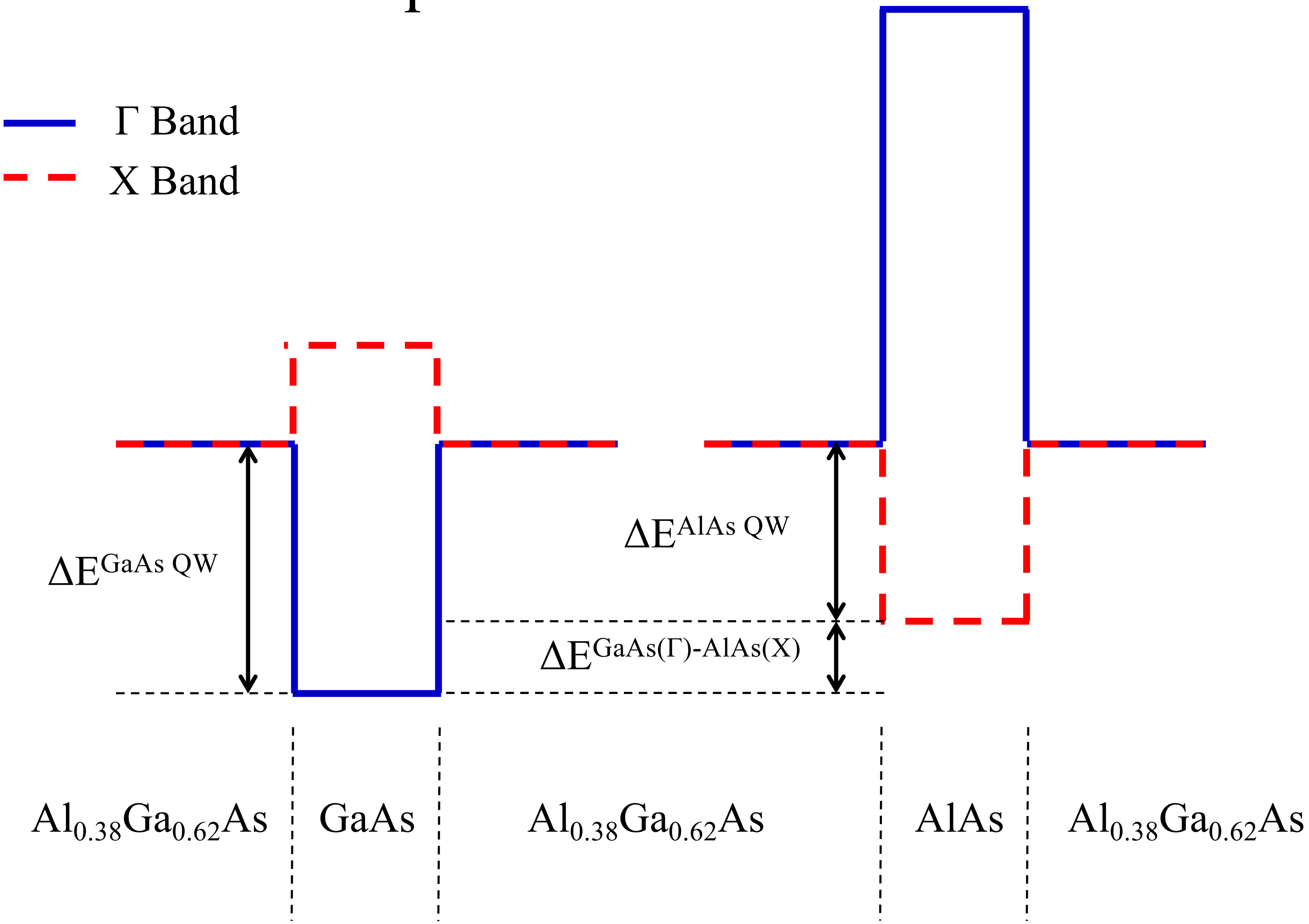
$$\therefore \Delta E_C - E_D \simeq \frac{ne^2 s}{\epsilon_0 \epsilon_b}$$

$$n \propto \Delta E_C - E_D$$

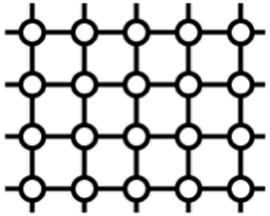


GaAs and AlAs quantum wells

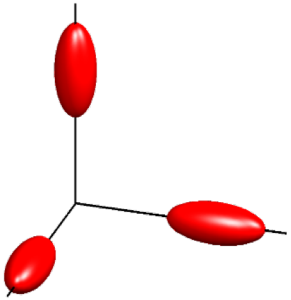


Valley occupation in AlAs quantum wells

Bulk

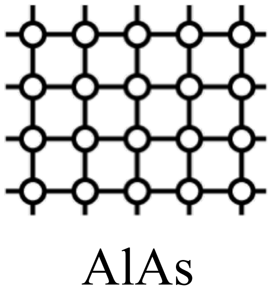


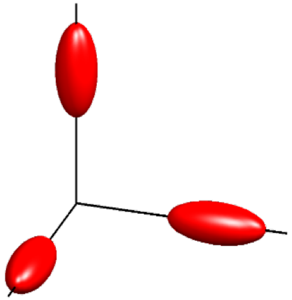
AlAs



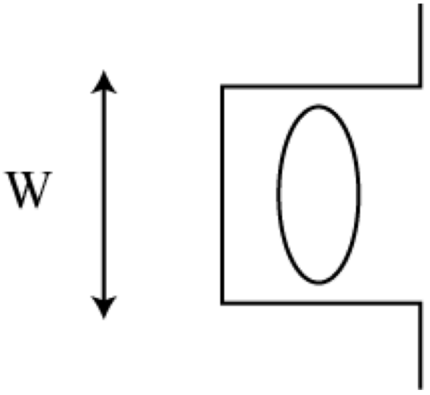
Valley occupation in AlAs quantum wells

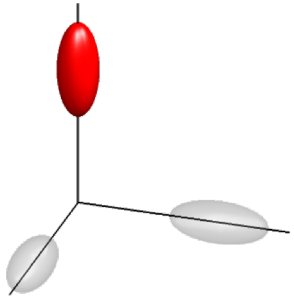
Bulk



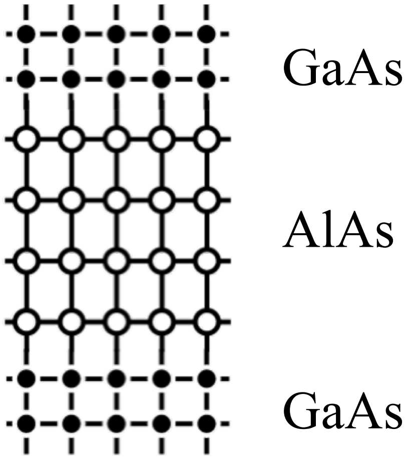


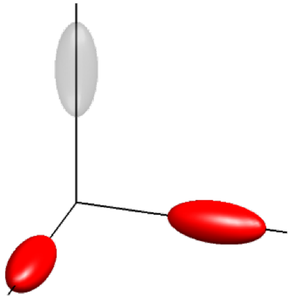
Narrow wells W < 60Å



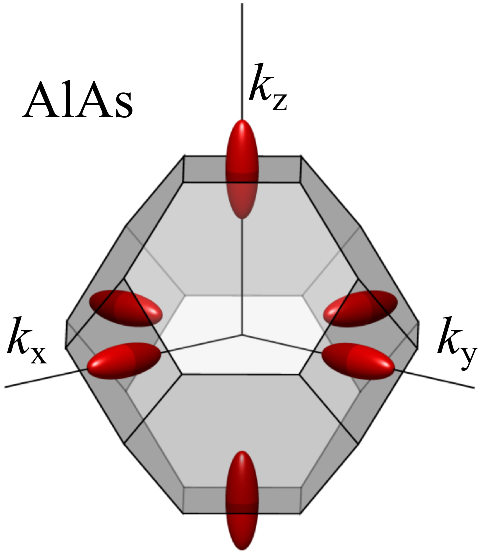


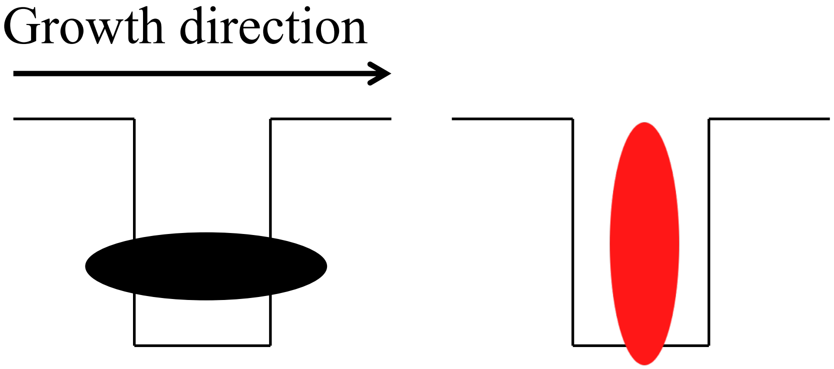
Wide wells W > 60Å





Valley occupation in AlAs quantum wells



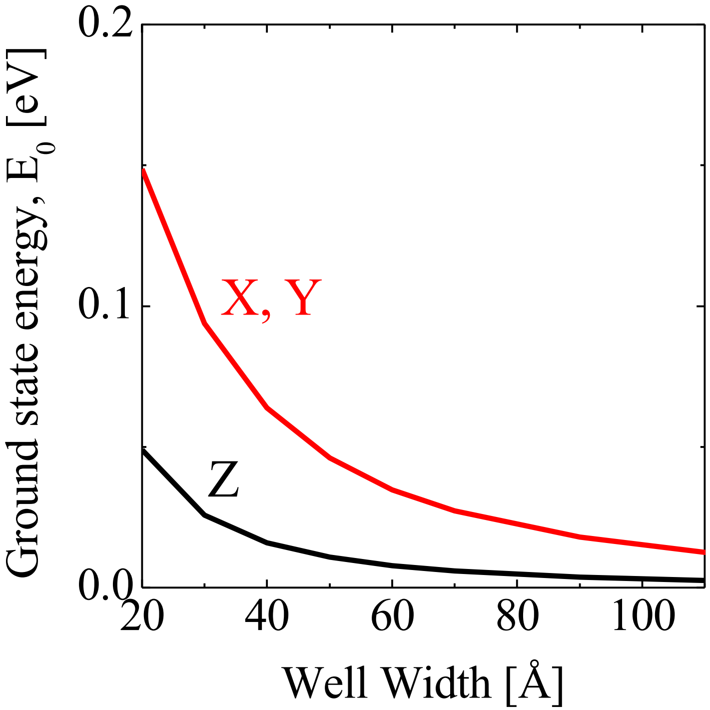


Z Valley

$m^* = 1.1\ m_e$

X, Y Valley

$m^* = 0.2\ m_e$



Valley occupation in AlAs quantum wells

	GaAs	AlAs
Lattice constant (at 300 K)	5.6533Å	5.6605Å

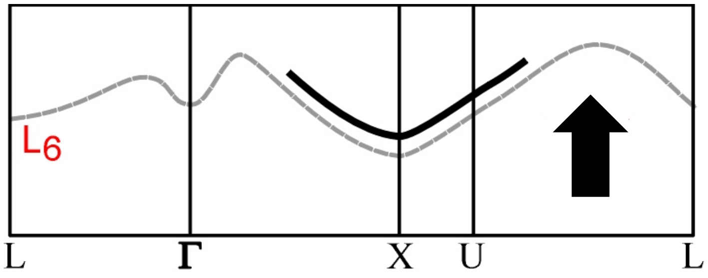
$$e_{\|} = e_{xx} = e_{yy} = \frac{a_{GaAs}-a_{AlAs}}{a_{AlAs}} = -1.8 \times 10^{-3}$$

$$e_{\perp} = e_{zz} = -2\frac{C_{12}}{C_{11}}e_{\|} = 1.7 \times 10^{-3}$$

$$\Xi = 5.6eV$$

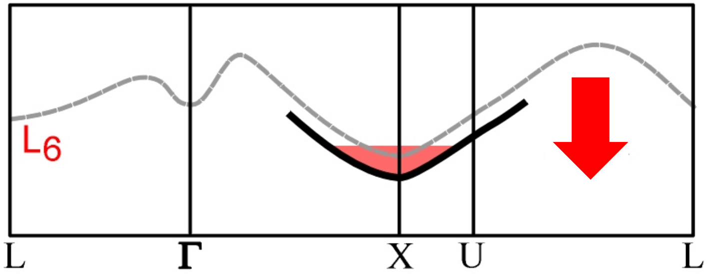
$$\Delta E_V = \Xi(e_{\|} - e_{\perp}) \simeq 20 \text{ meV}$$

Z Valley

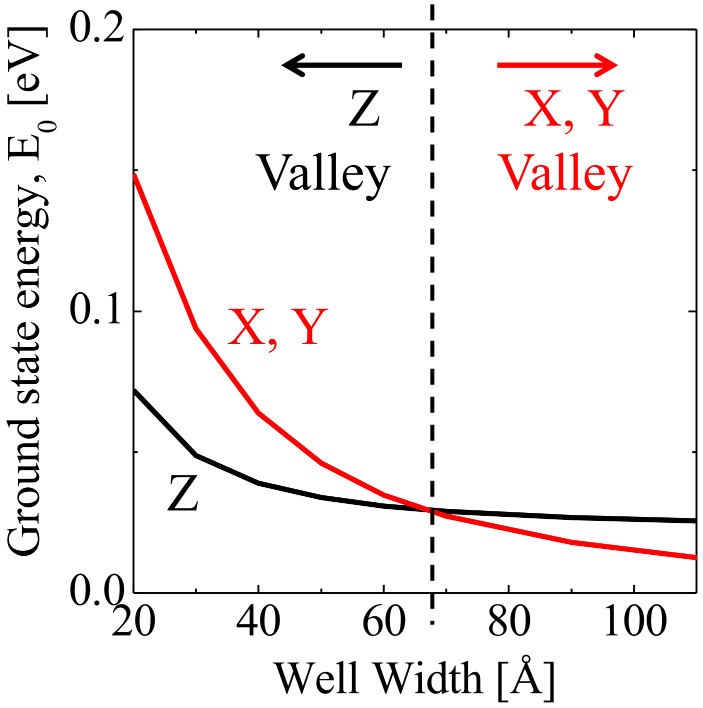


TENSILE STRAIN

X,Y Valley



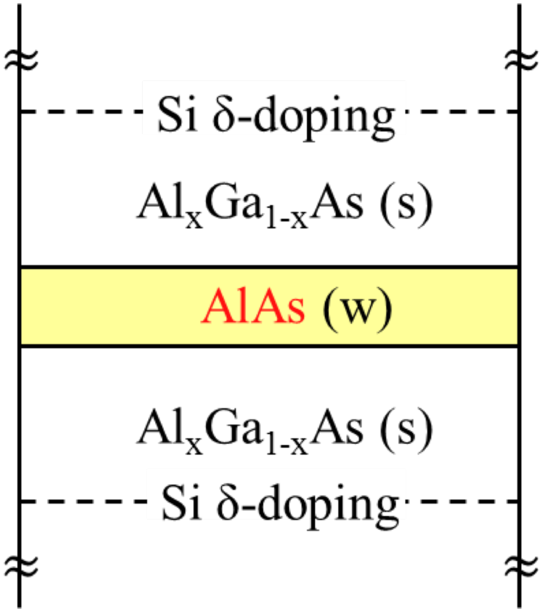
COMPRESSIVE STRAIN



H. W. van Kesteren et al., Phys. Rev. B **39**, 13 426 (1989)

Motivation

‘Standard’ AlAs sample



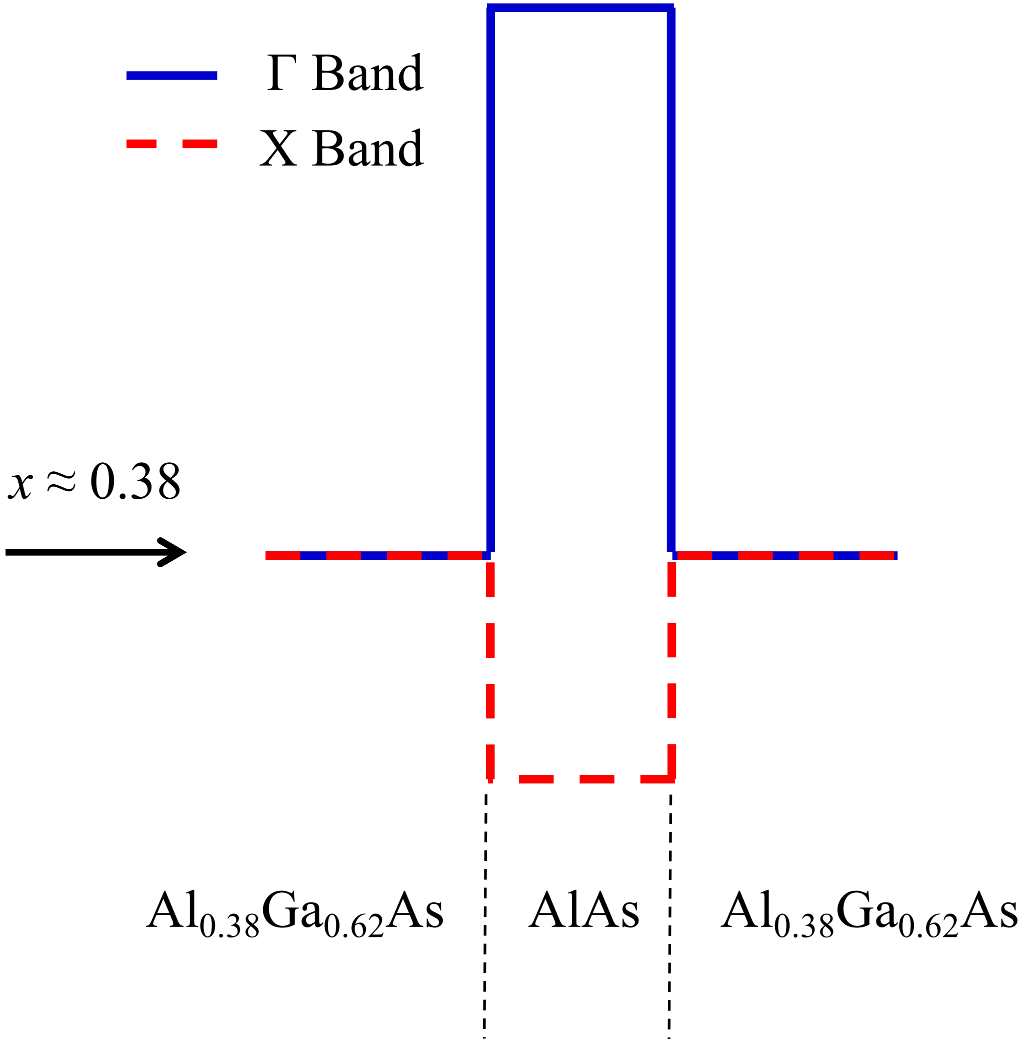
Si δ-doping

$Al_xGa_{1-x}As$ (s)

AlAs (w)

$Al_xGa_{1-x}As$ (s)

Si δ-doping



$x \approx 0.38$

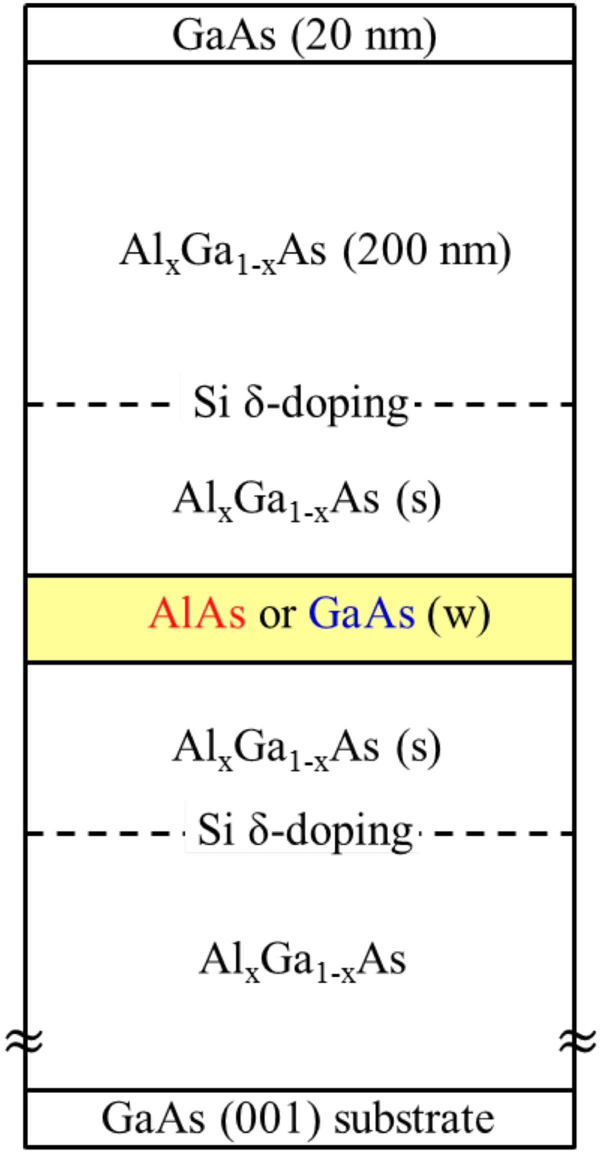
Γ Band

X Band

$Al_{0.38}Ga_{0.62}As$ AlAs $Al_{0.38}Ga_{0.62}As$

Is this the only possible structure?

Sample structure



GaAs (20 nm)

$Al_xGa_{1-x}As$ (200 nm)

Si δ-doping

$Al_xGa_{1-x}As$ (s)

AlAs or GaAs (w)

$Al_xGa_{1-x}As$ (s)

Si δ-doping

$Al_xGa_{1-x}As$

GaAs (001) substrate

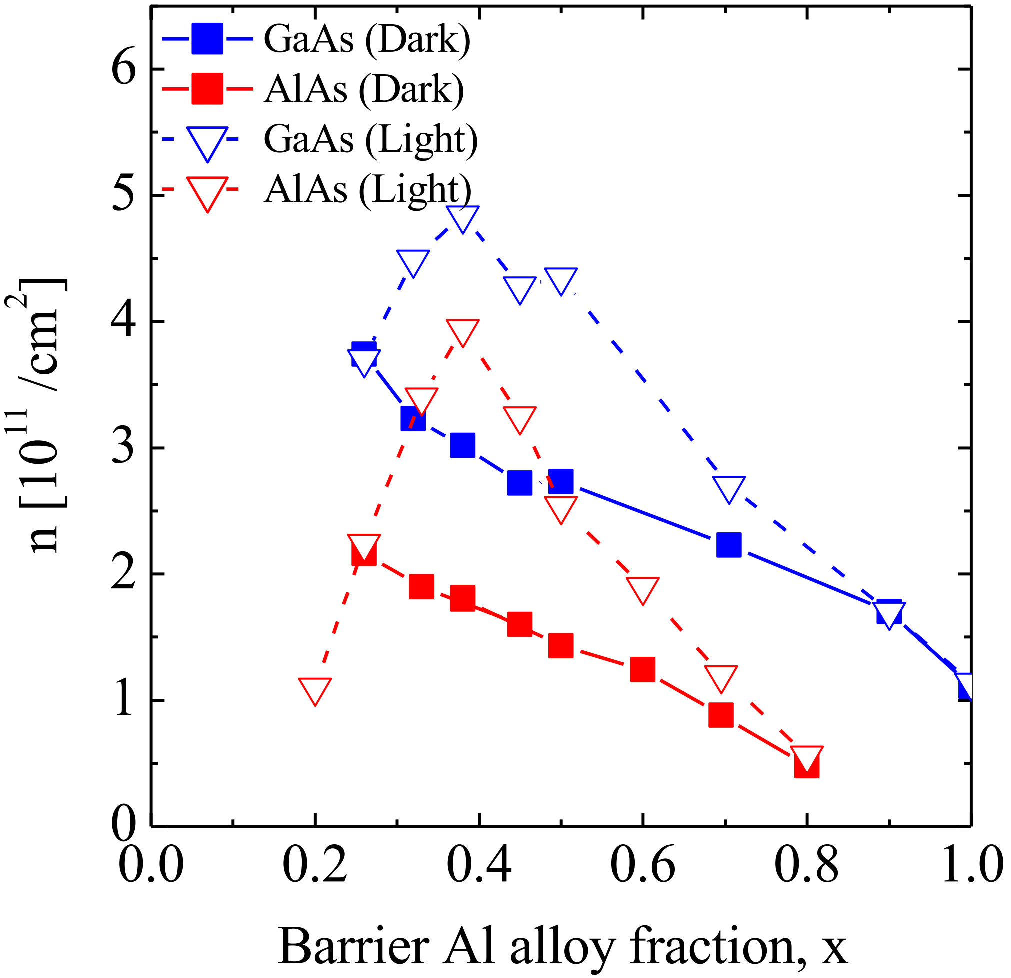
Molecular beam epitaxy

$T_{sub} = 645$ ℃

GaAs samples	AlAs samples
$s = 70$ nm	$s = 59$ nm
$0.26 \leq x \leq 1.0$	$0.20 \leq x \leq 0.80$
$w = 20$ nm	$w = 11$ nm

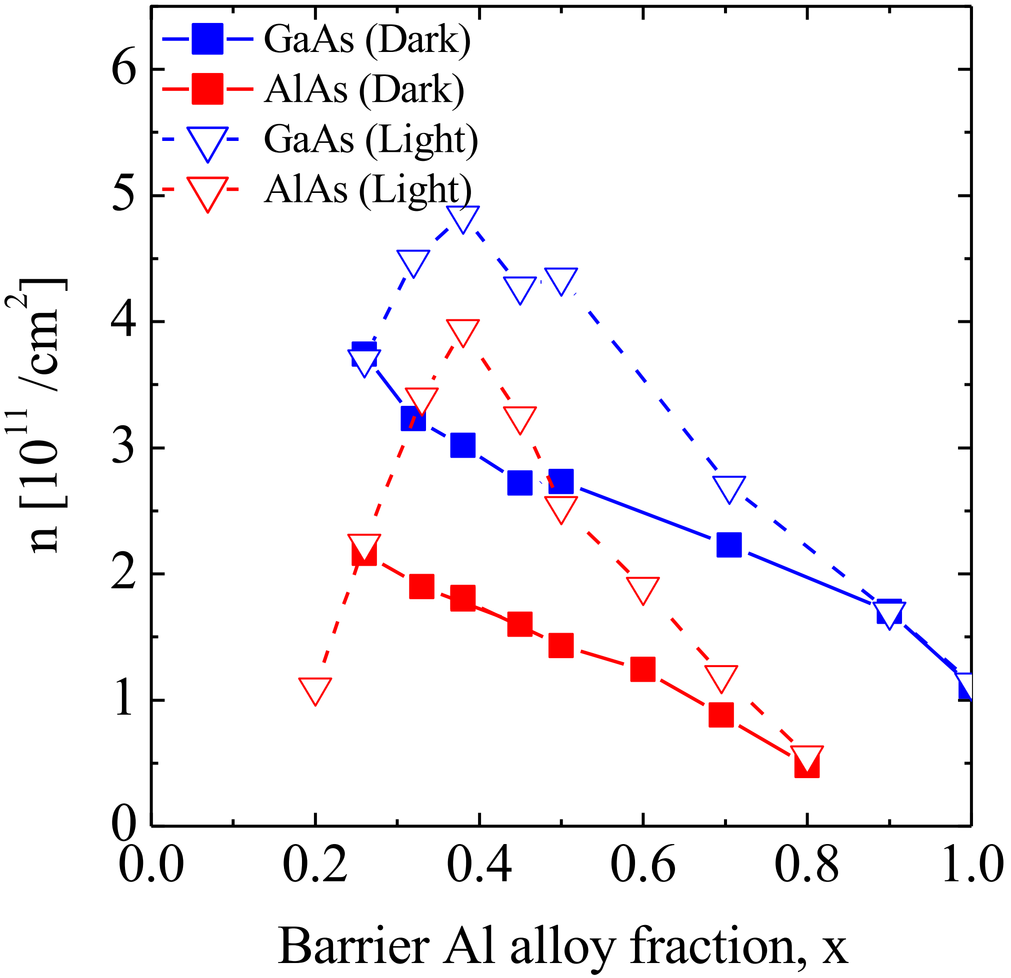
Magnetotransport
Van der Pauw at 0.3 K

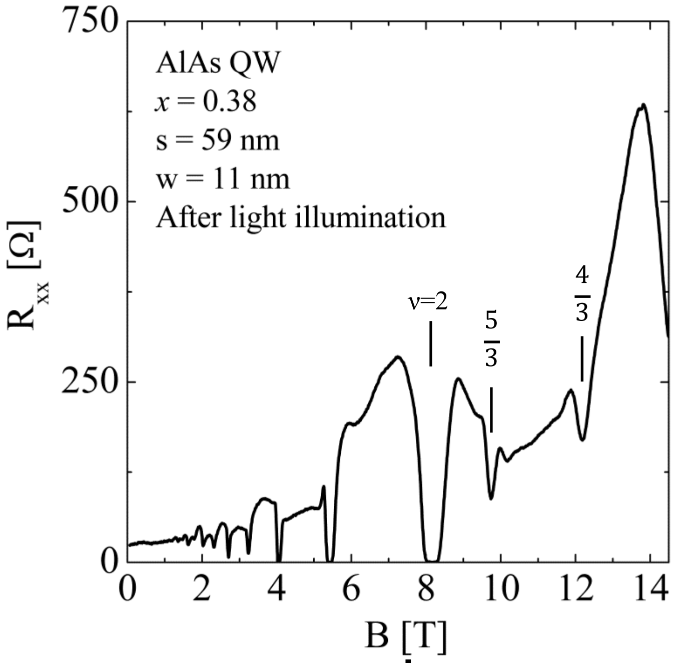
2DES density vs barrier alloy fraction



Y. J. Chung, Phys. Rev. Mater. **1**, 021002(R) (2017)

2DES density vs barrier alloy fraction



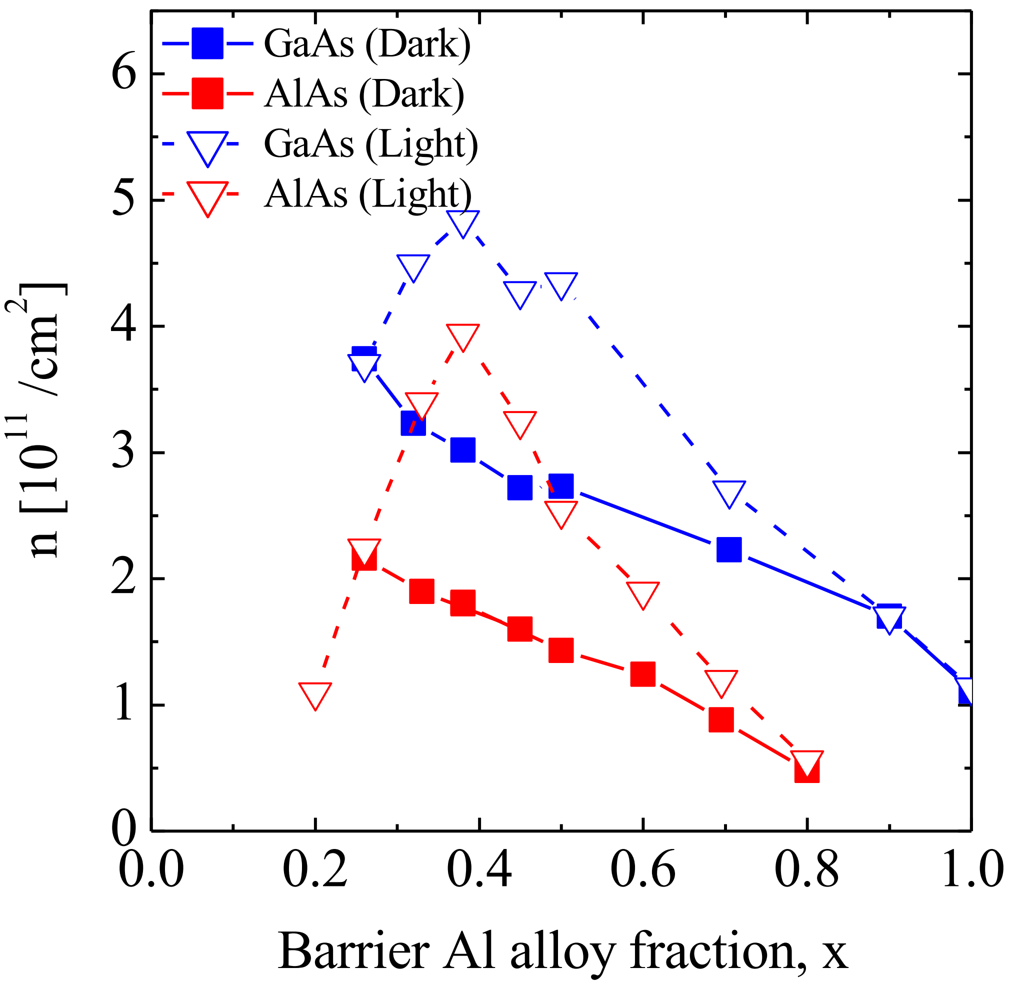


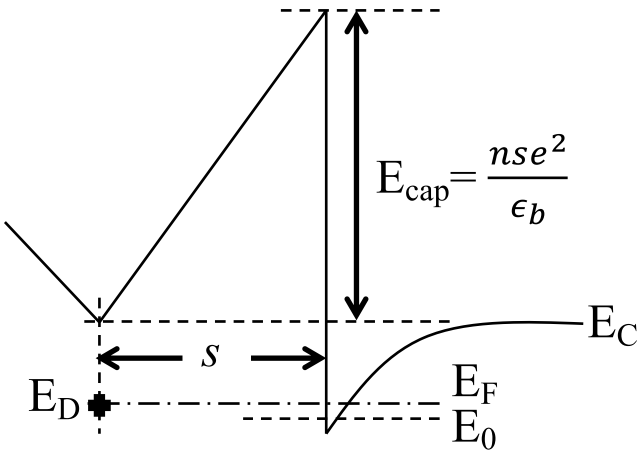
$n = 3.9 \times 10^{11}$ /cm^2

$$\nu = \frac{h}{e}\frac{n}{B}$$ Quantum Hall sequence

- Each data point measured from magnetoresistance
- Qualitative trend similar for GaAs and AlAs

2DES density vs barrier alloy fraction





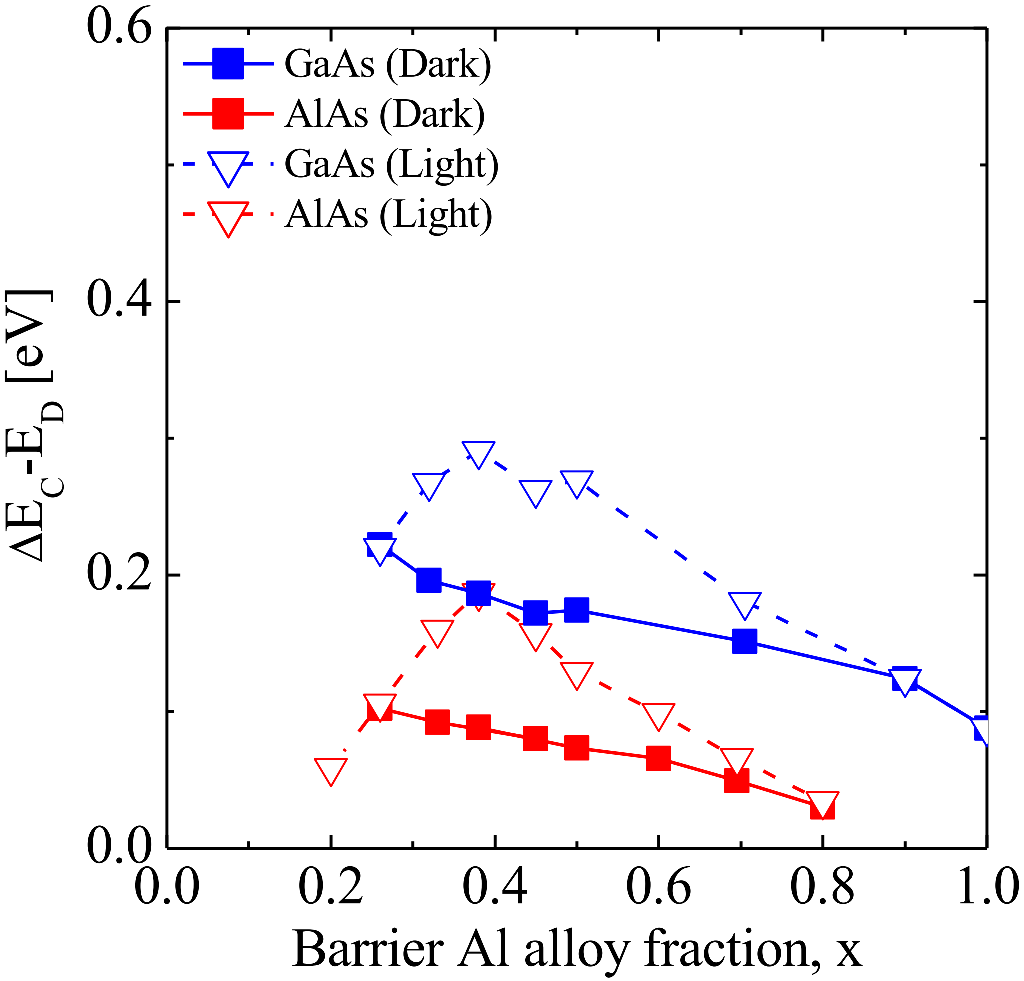
$$\Delta E_C = E_0 + E_F + E_D + \frac{e^2 sn}{\epsilon_0 \epsilon_b}$$

$$n = \frac{1}{s} \frac{\varepsilon_0 \varepsilon_b (\Delta E_c - E_D - (E_F + E_0))}{e^2}$$

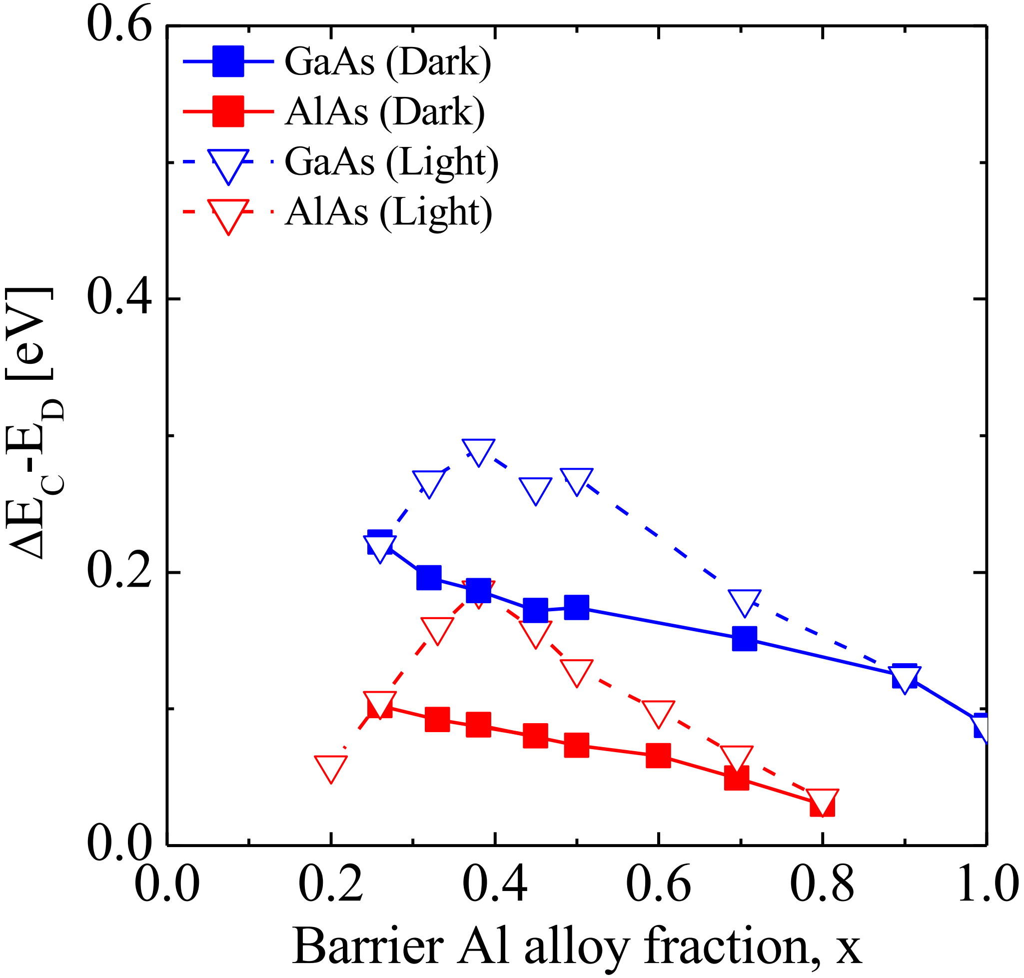
(×2 for double-sided-doped QW)

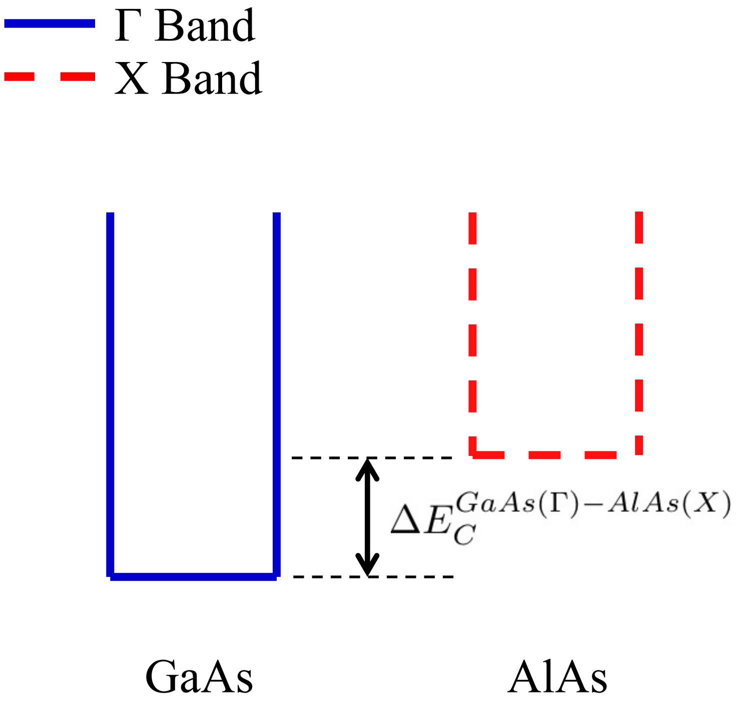
- Each data point measured from magnetoresistance
- Qualitative trend similar for GaAs and AlAs

Donor energy levels vs barrier alloy fraction

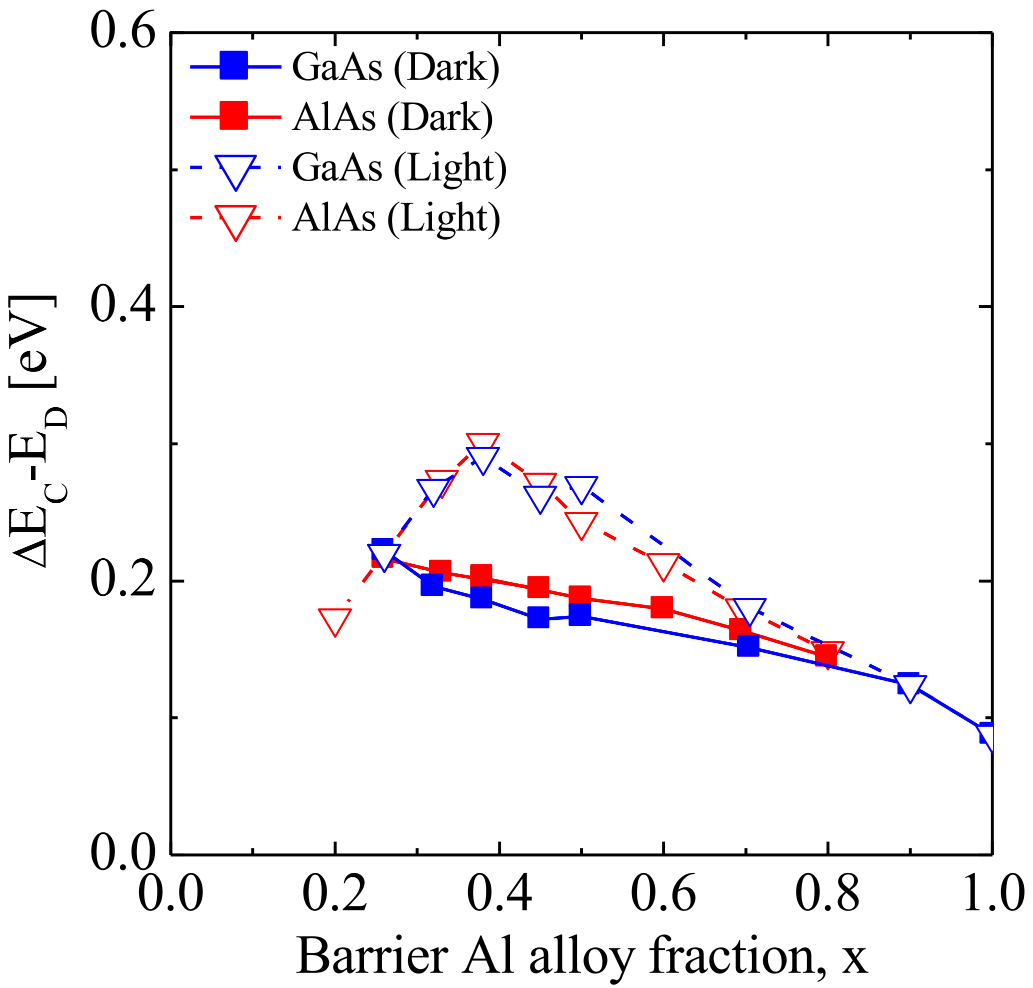


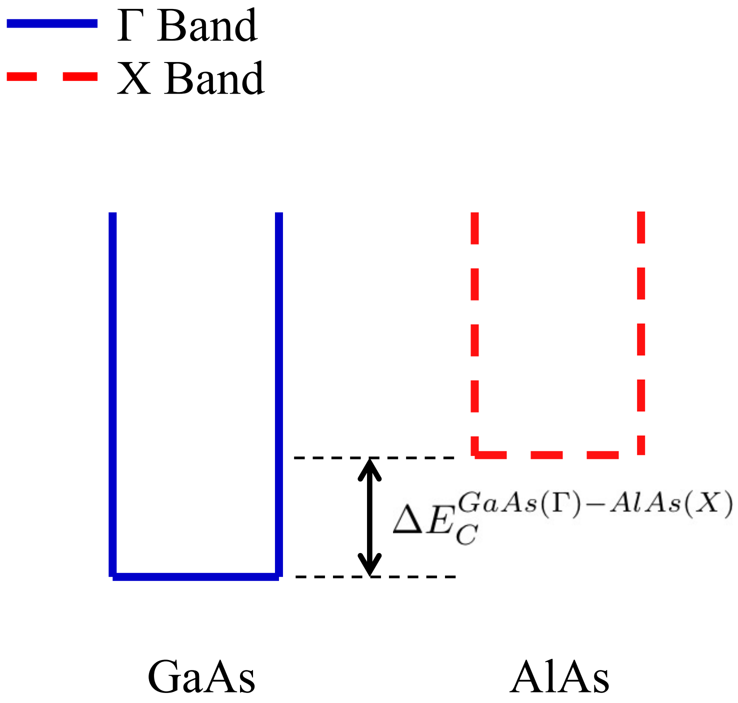
Donor energy levels vs barrier alloy fraction





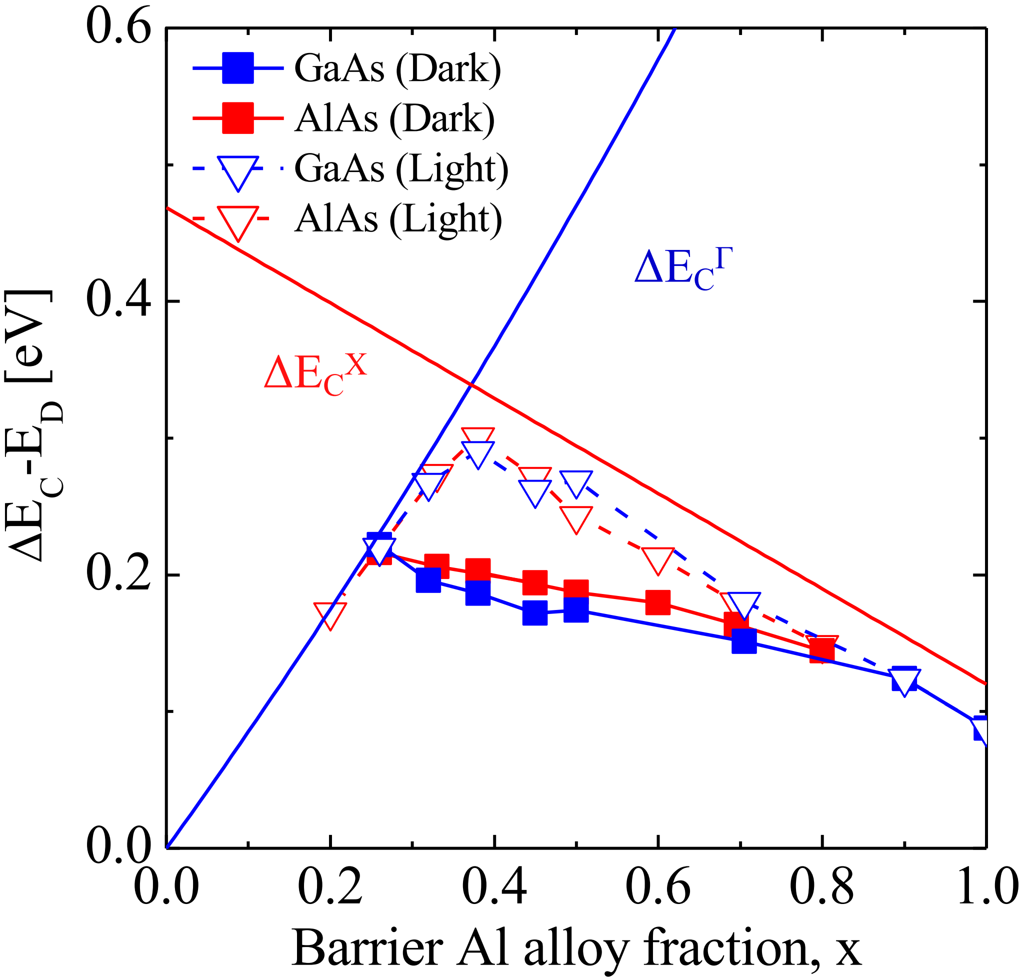
Donor energy levels vs barrier alloy fraction





Take $\Delta E_C^{\mathrm{GaAs(\Gamma)\text{-}AlAs(X)}} = 115$ meV
Good agreement between
AlAs and GaAs

Donor energy levels vs barrier alloy fraction

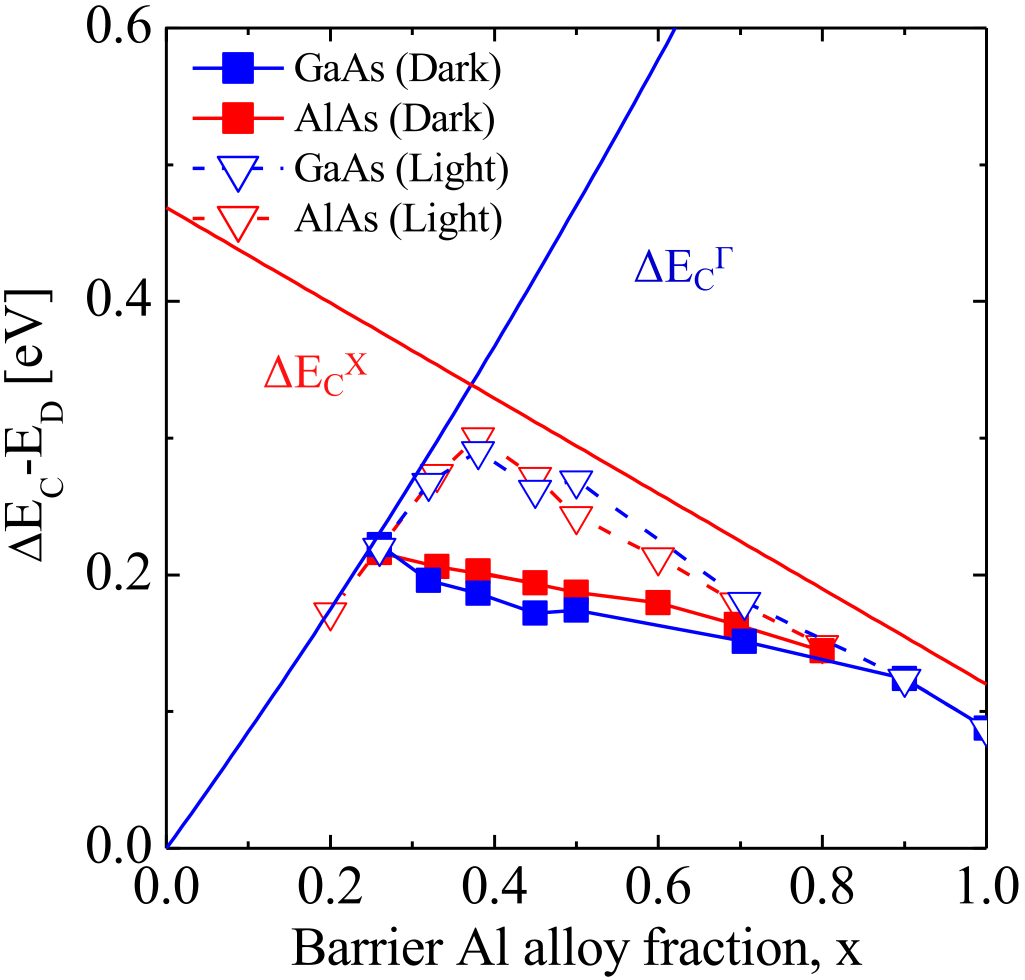


- Band edges estimated assuming hydrogenic donor levels for the results after illumination roughly coincide with values reported in literature

- For both AlAs and GaAs;
  $x < 0.38$: doping from Γ band
  $x > 0.38$: doping from X band

S. Adachi, J. Appl. Phys. **58**, R1 (1985)
I. Vurgaftman et. al., J. Appl. Phys. **89**, 5815 (2001)

Donor energy levels vs barrier alloy fraction



- Band edges estimated assuming hydrogenic donor levels for the results after illumination roughly coincide with values reported in literature
- For both AlAs and GaAs;
  $x < 0.38$: doping from Γ band
  $x > 0.38$: doping from X band

➡ Same rules that govern modulation doping in GaAs 2DESs can be applied to AlAs 2DESs

Outline

- Introduction
  - Clean 2DESs and the GaAs/AlAs materials group
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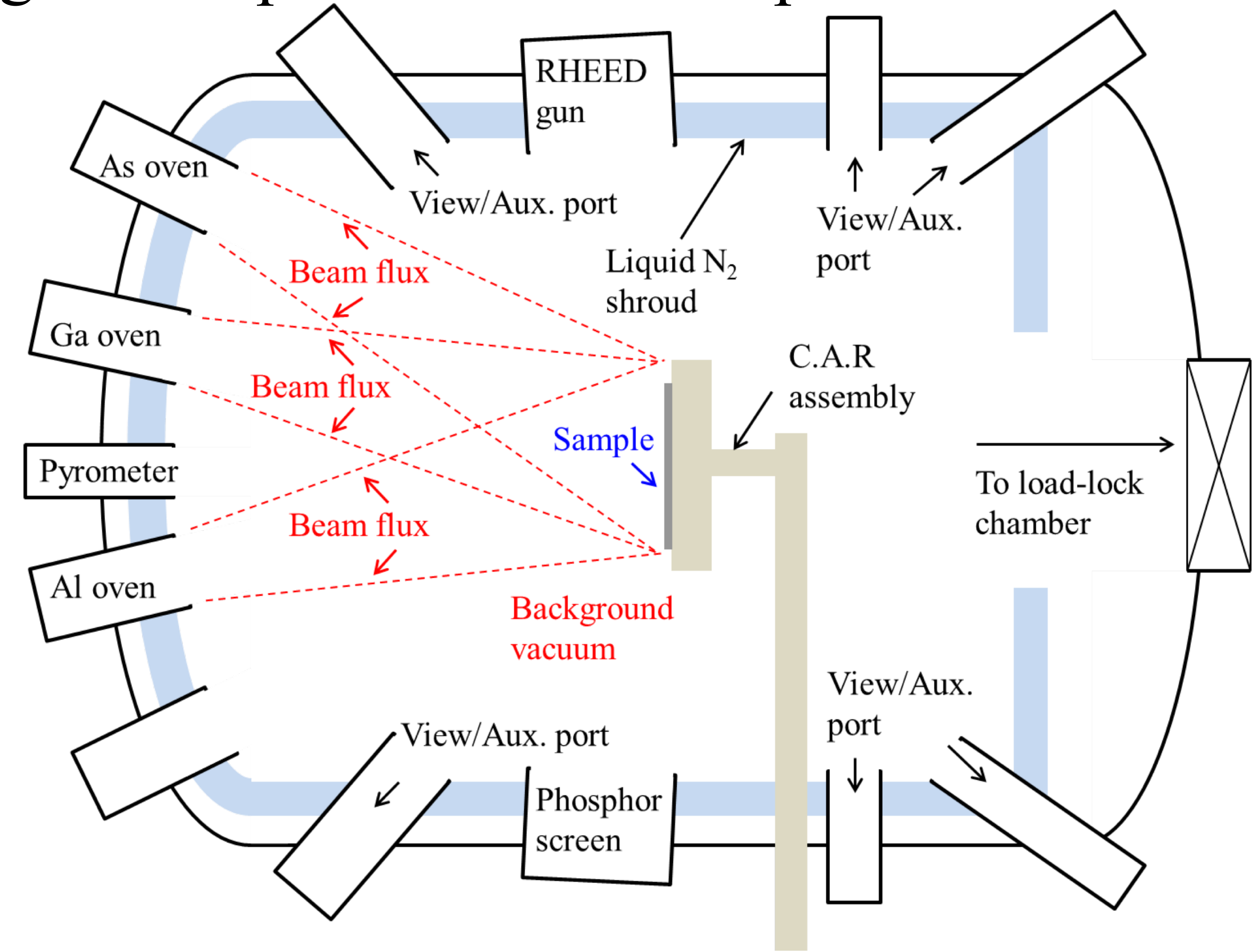
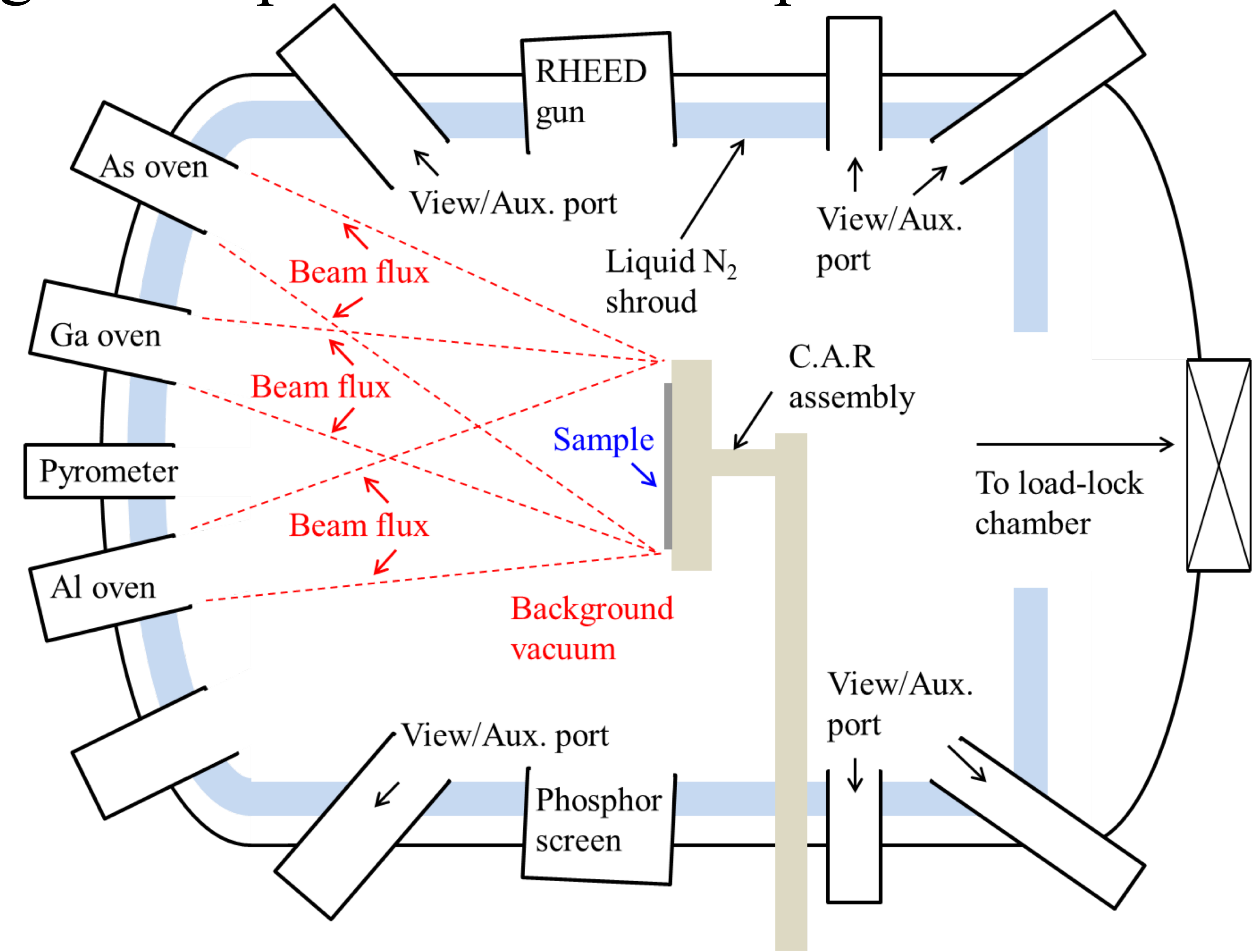
  - Defining GaAs and AlAs 2DESs
  - Systematic impurity reduction
  - Record-quality AlAs and GaAs 2DESs
- Summary

Origin of impurities in the sample

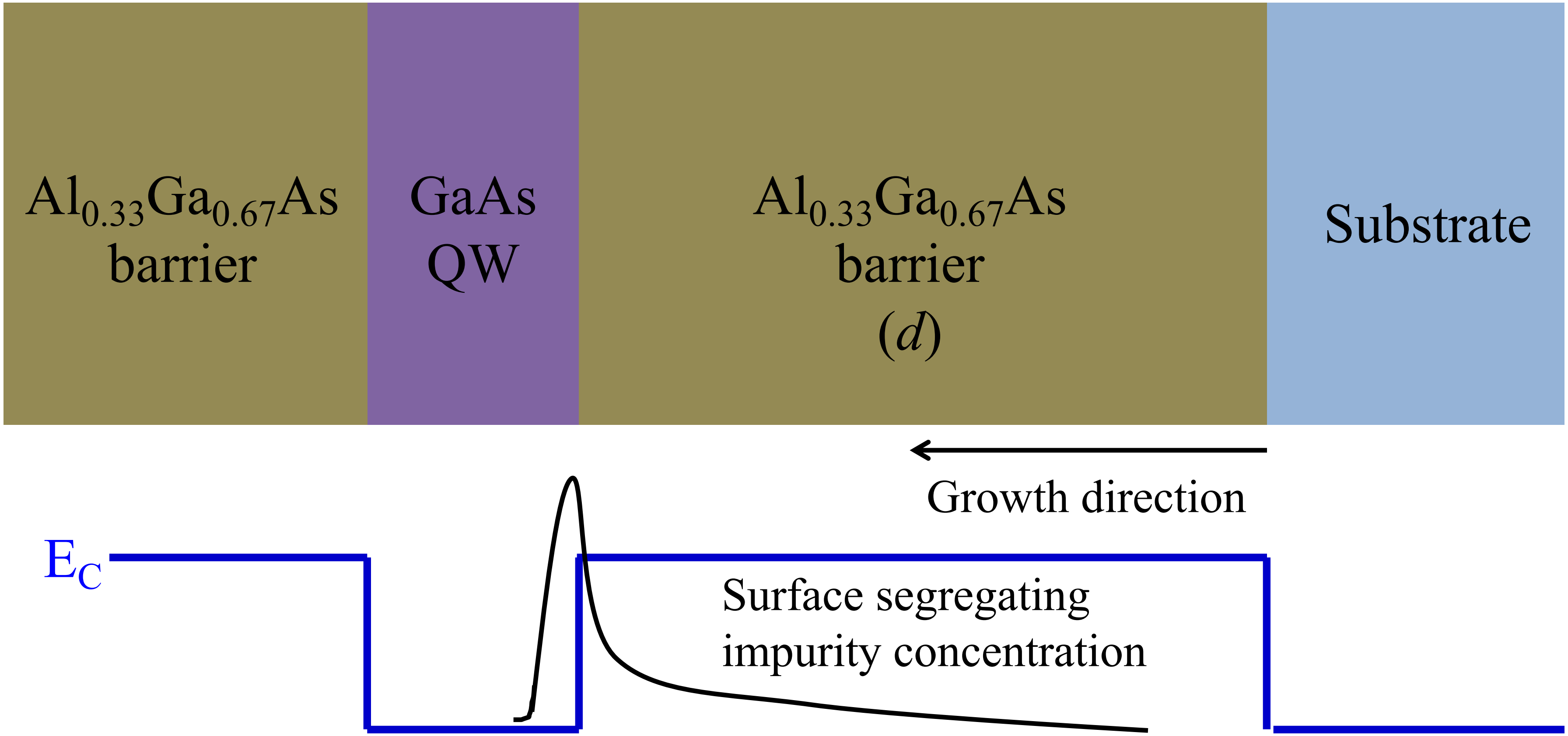


Origin of impurities in the sample



- Offline bakes of source material
- Improve MBE hardware

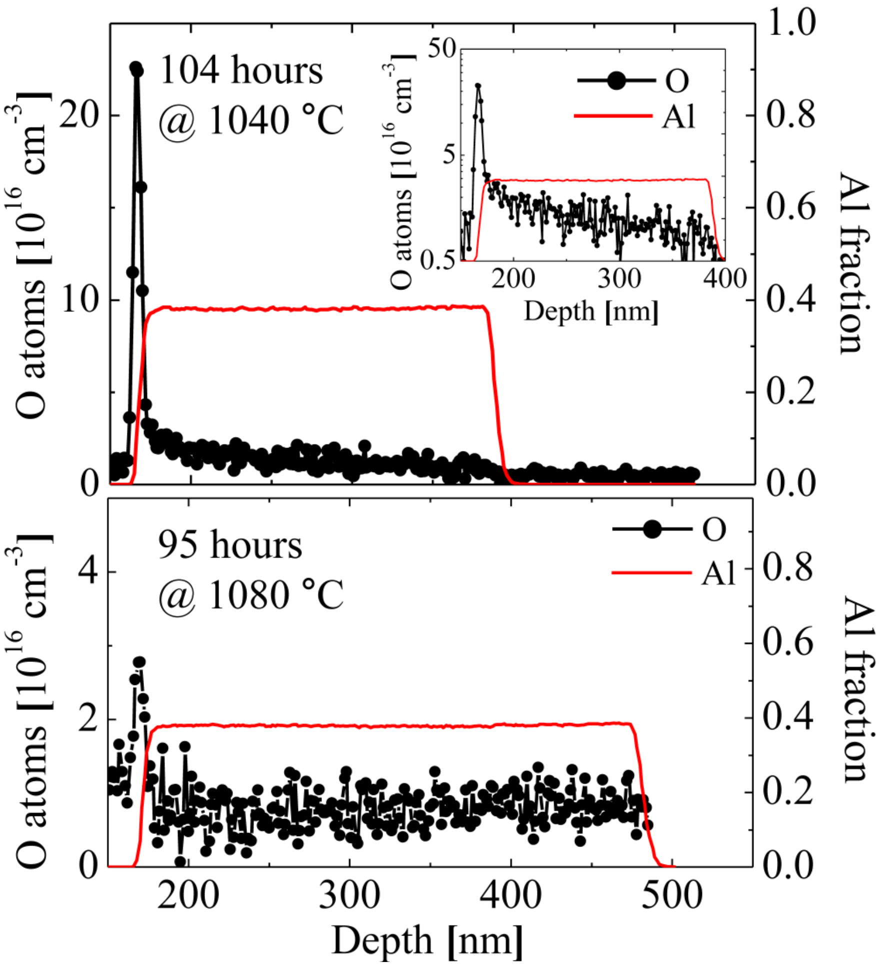
Quantifying impurities in the growth space

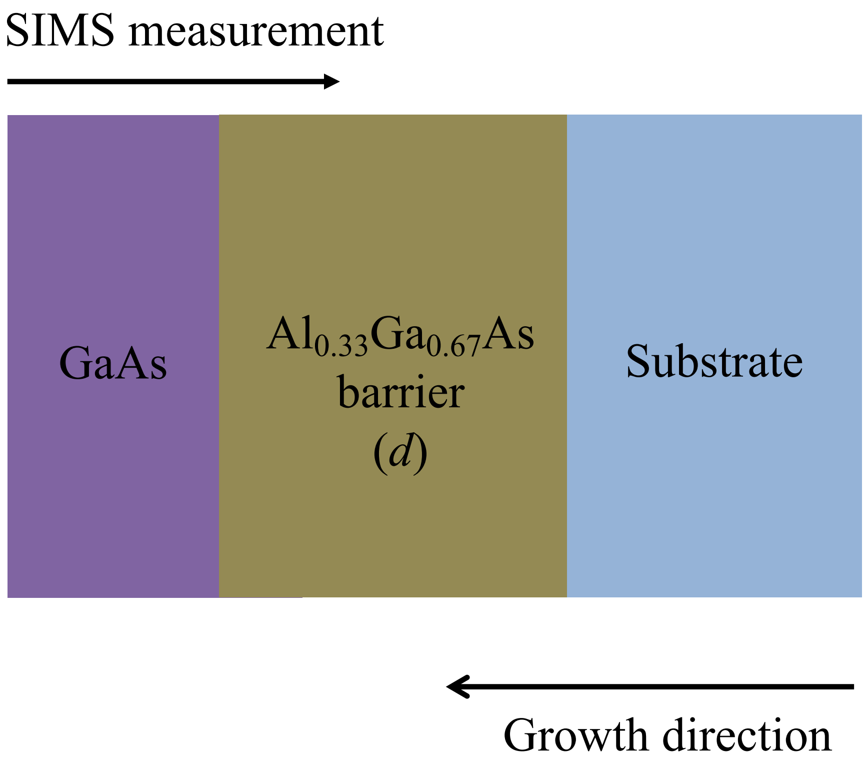


Y. J. Chung, Phys. Rev. Mater. **2**, 034006 (2018)

- ‘Snow plow’ of impurities occurs in growth direction
- Measure mobility in GaAs quantum well

Confirming surface segregation via SIMS





SIMS measurement

GaAs

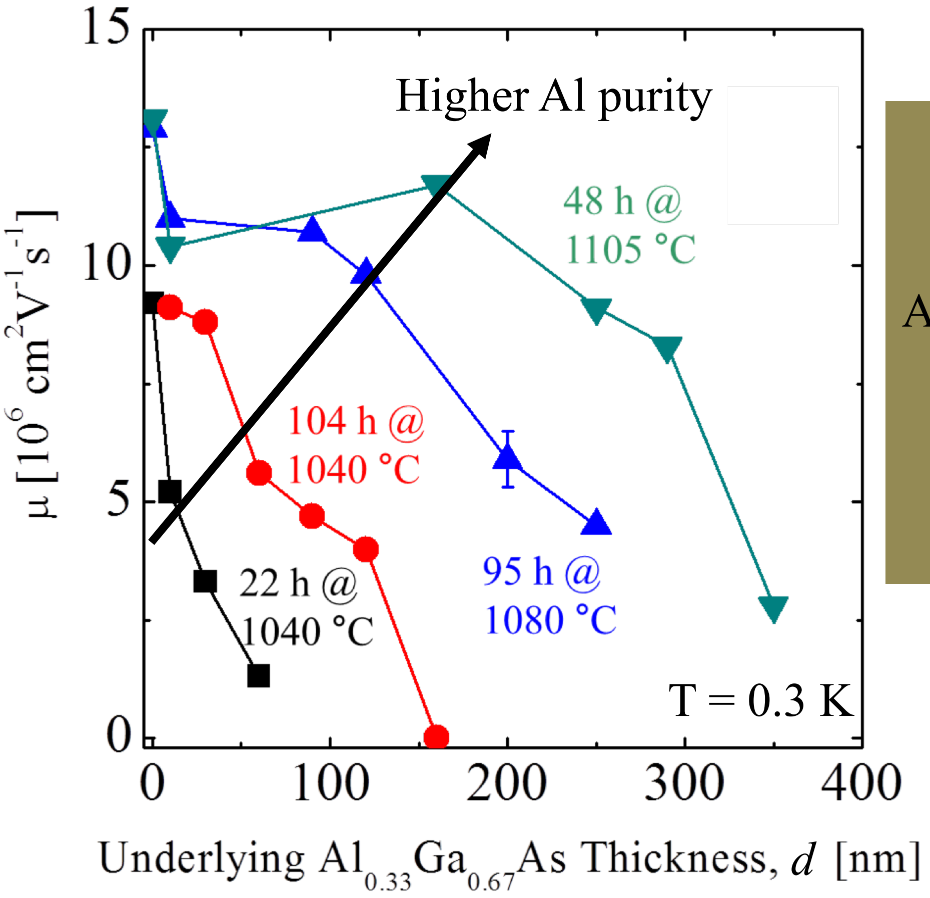
$Al_{0.33}Ga_{0.67}As$
barrier
(*d*)

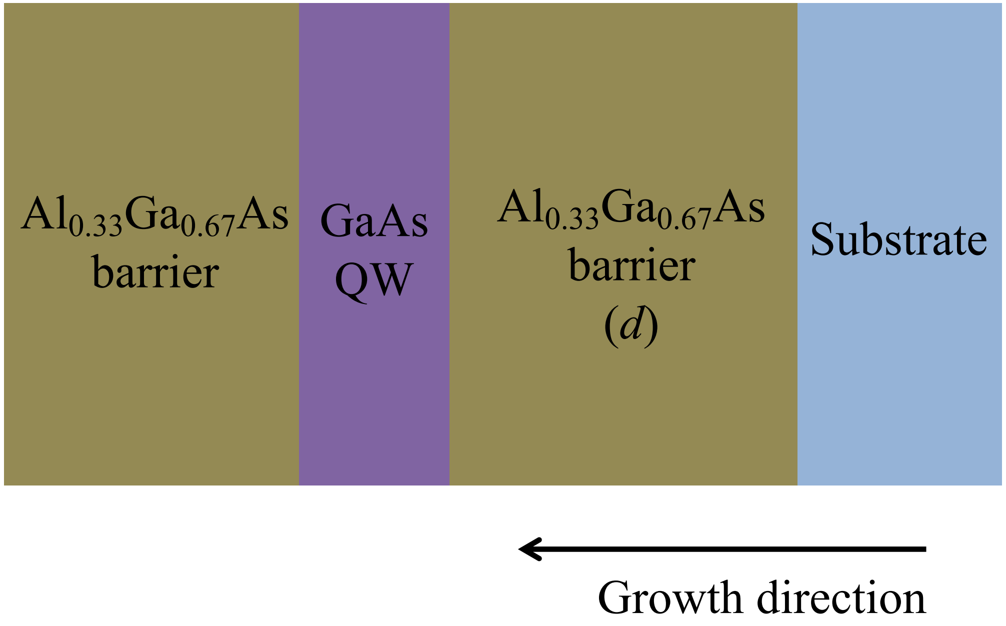
Substrate

Growth direction

- SIMS confirms surface segregation structure works

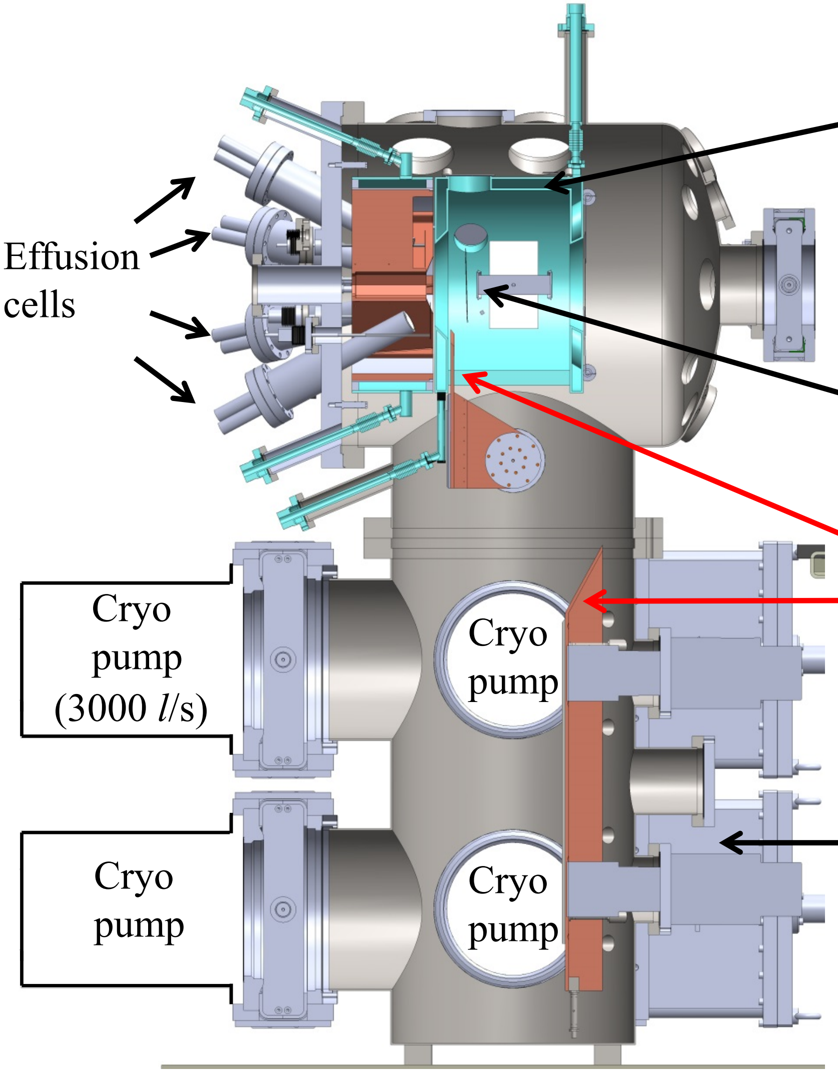
Quantifying Al purity





- μ is more sensitive than chemical analysis due to detection limits

Improving vacuum in the MBE chamber



Liquid N_2
shroud
(~77 K)

Effusion
cells

To load-lock
chamber

Growth
space

Ni-coated
Cu cold
plates
(~17 K)

Cryo
pump
(3000 *l*/s)

Cryo
pump

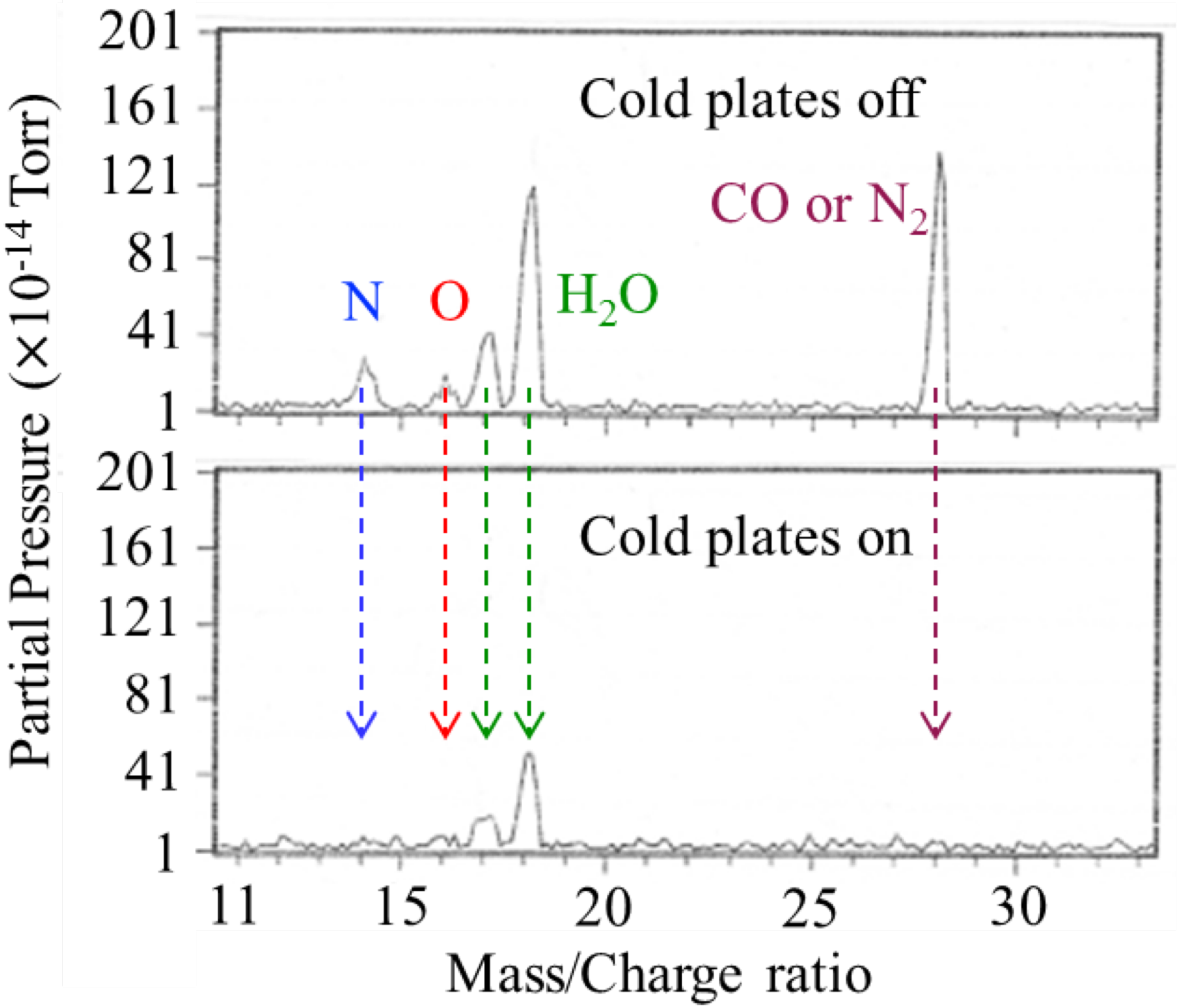
Cryo
pump

Cryo
pump

Gate
valve

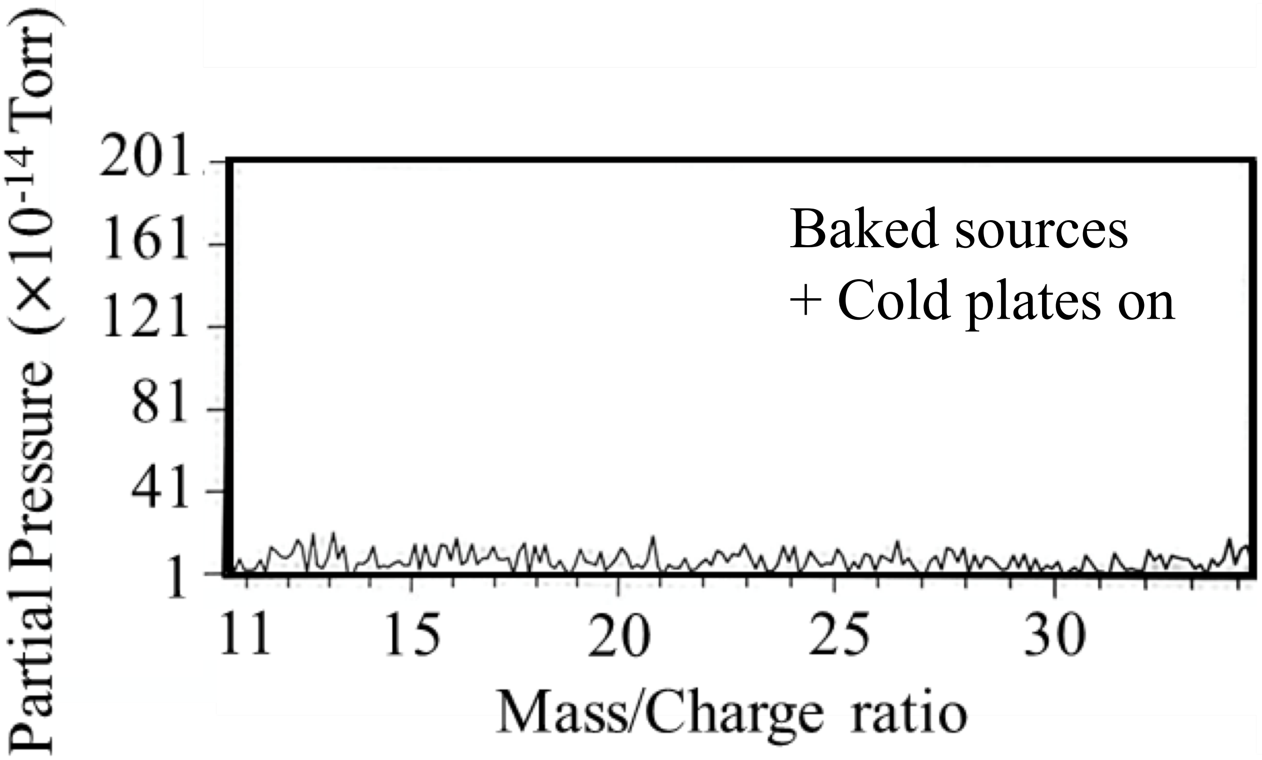
Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Improving vacuum in the MBE chamber



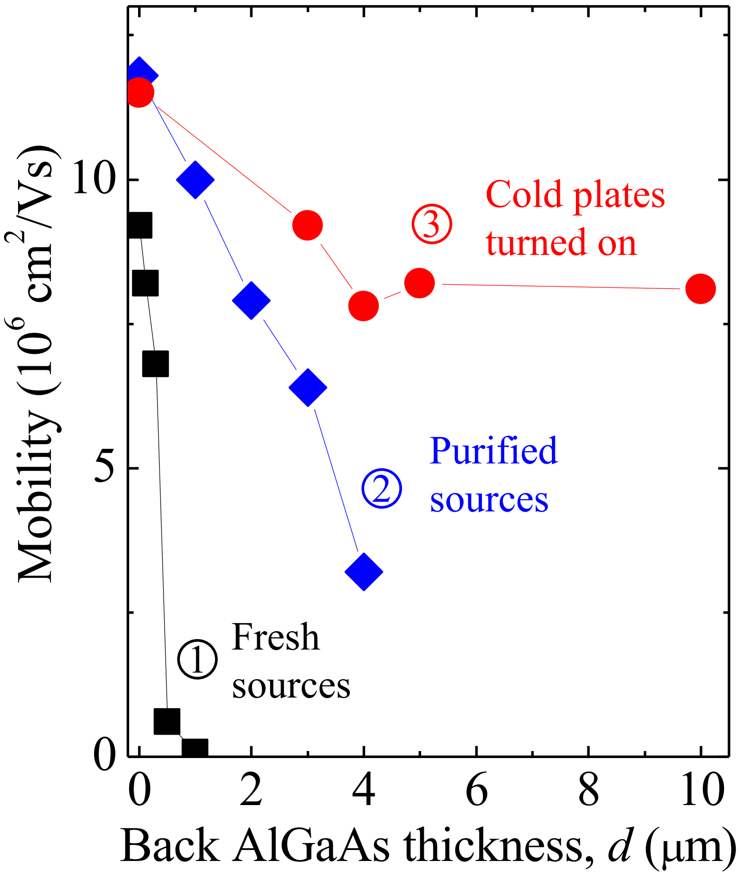
- RGA spectrum shows significant reduction in O, H_2O, and N related species in the growth environment

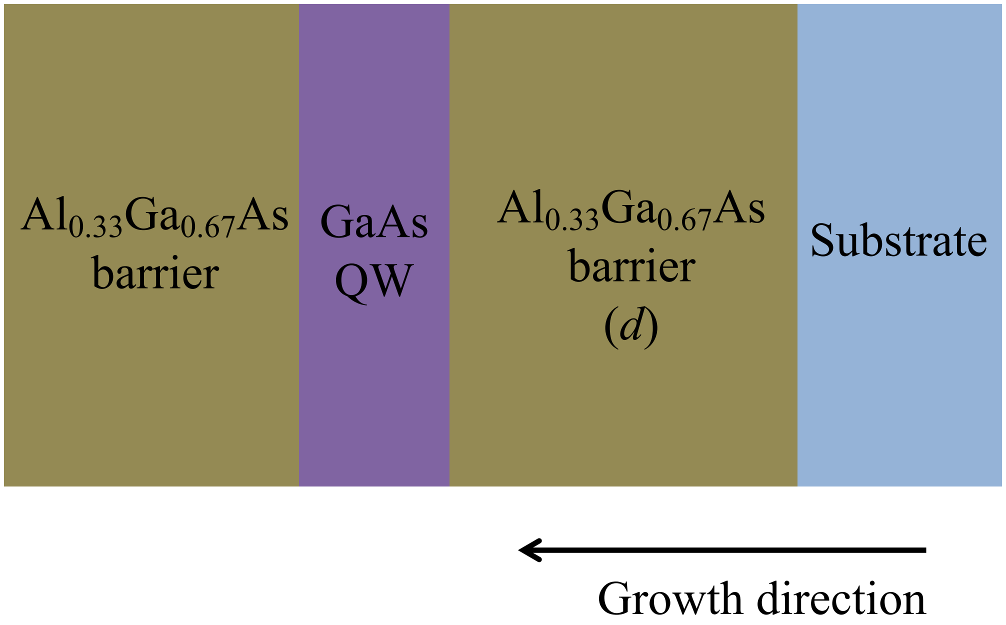
Improving vacuum in the MBE chamber



- With sufficiently baked out sources, the partial pressures of these species are further reduced to virtually nothing

Quantifying vacuum quality





$Al_{0.33}Ga_{0.67}As$ barrier

GaAs QW

$Al_{0.33}Ga_{0.67}As$ barrier (*d*)

Substrate

Growth direction

- The mobility of this structure can be used as a probe of vacuum quality
- Confirms that improved vacuum reduces the amount of impurities in structure

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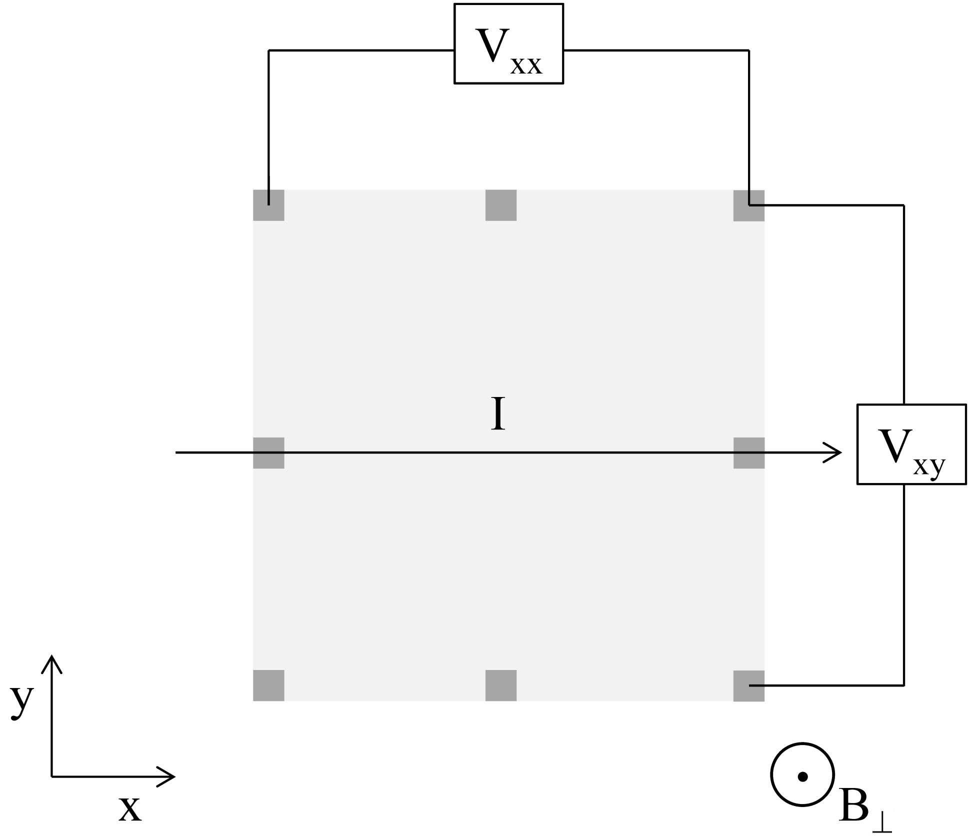
- Summary

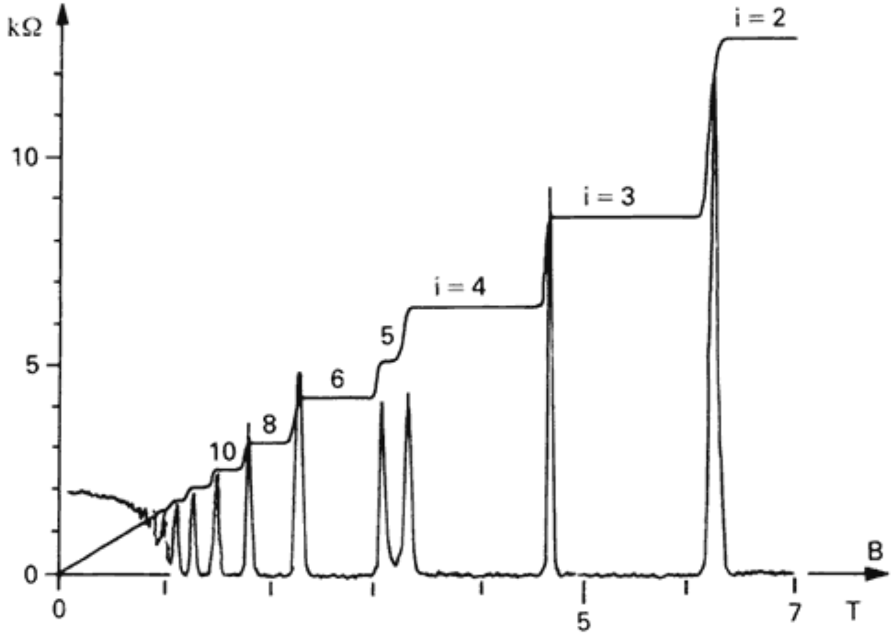
Magnetotransport in 2DESs

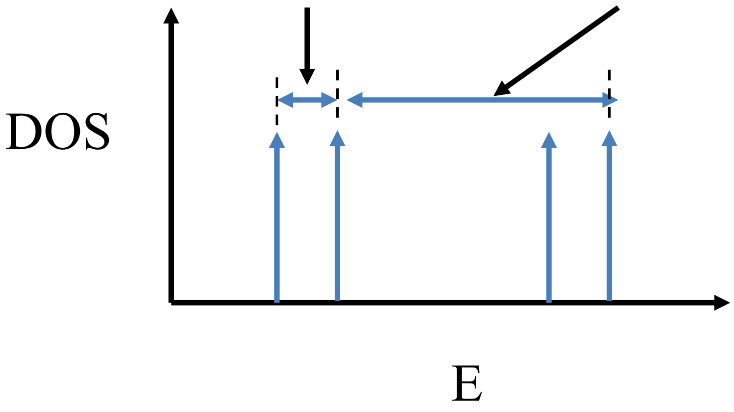


$$R_{xx} = \frac{V_{xx}}{I}$$

$$R_{xy} = \frac{V_{xy}}{I}$$

Integer quantum Hall effect





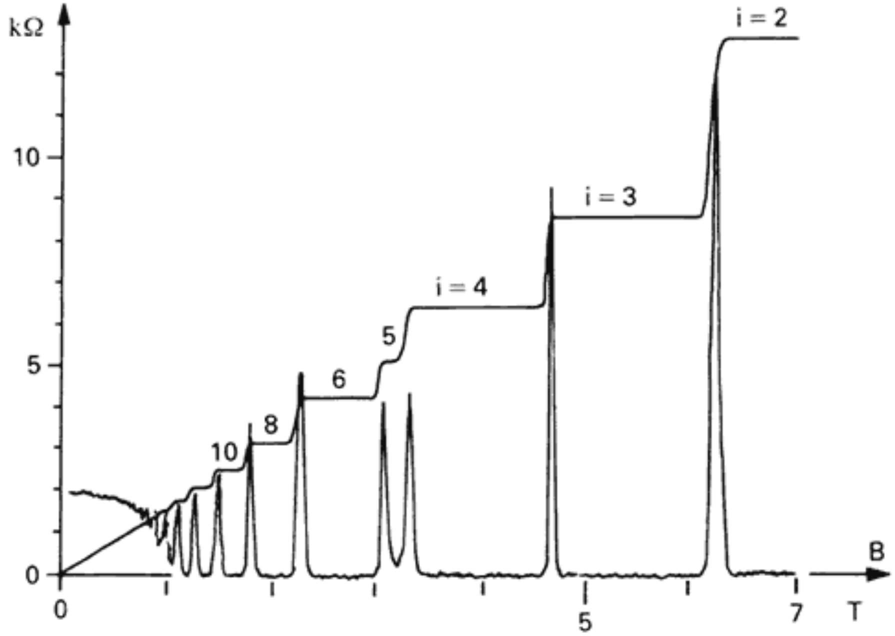
$$\Delta E_Z = g\mu_B B \qquad \Delta E_{cyc} = \frac{\hbar e B}{m^*}$$

Ideally Landau levels
should be delta functions

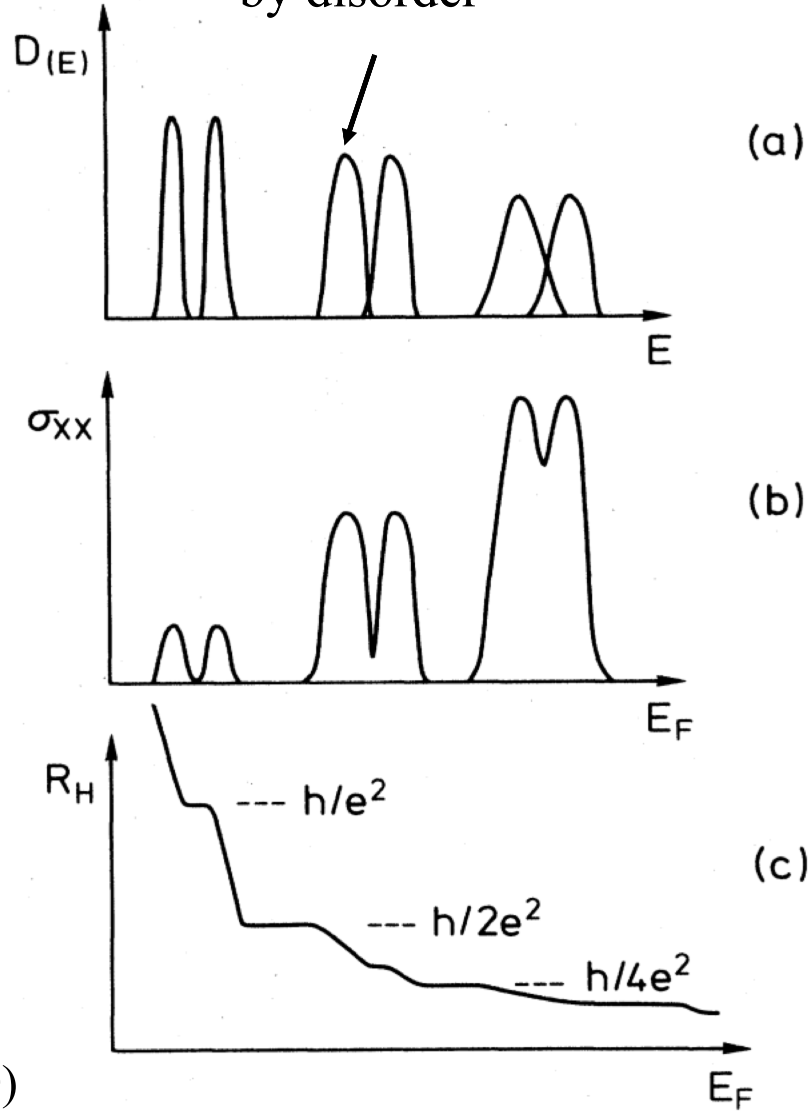
K. von Klitzing, Phys. Rev. Lett. 45 494 (1980)

K. von Klitzing, Rev. Mod. Phys. 58, 519 (1986)

Integer quantum Hall effect



Landau levels broadened by disorder



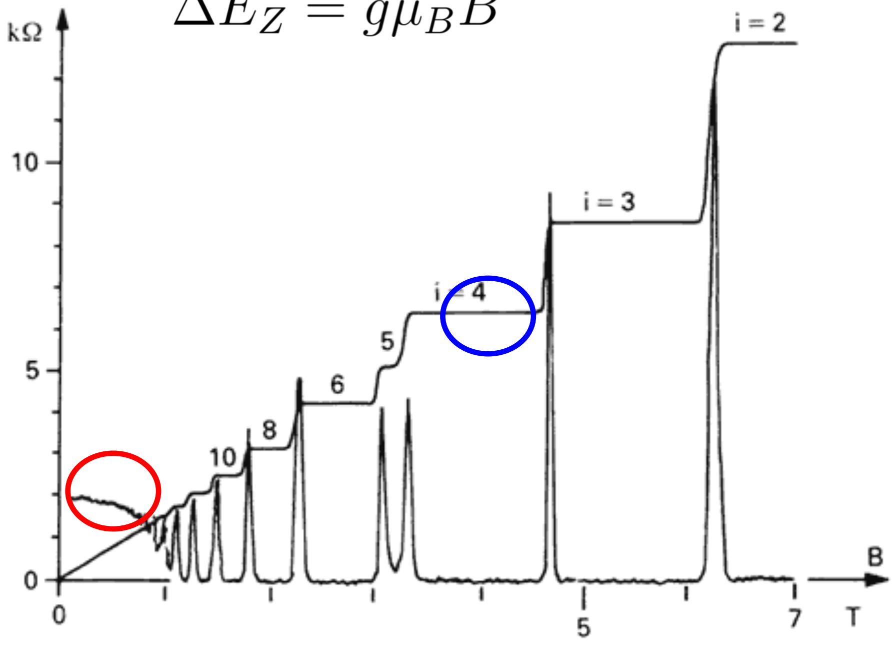
K. von Klitzing, Phys. Rev. Lett. 45 494 (1980)

K. von Klitzing, Rev. Mod. Phys. 58, 519 (1986)

Integer quantum Hall

$$\Delta E_{cyc} = \frac{\hbar e B}{m^*}$$

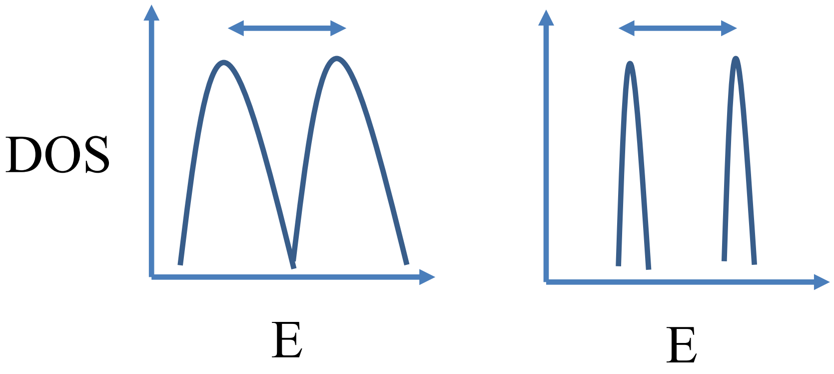
$$\Delta E_Z = g\mu_B B$$



Integer quantum Hall effect

K. von Klitzing, Phys. Rev. Lett. 45 494 (1980)

K. von Klitzing, Rev. Mod. Phys. 58, 519 (1986)



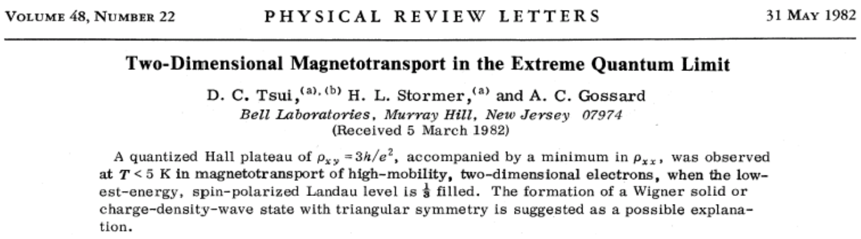
High disorder

Low disorder

What are signatures of a low-disorder (high-quality) sample?

- Should be able to discern different Landau levels at low field
- Should measure a large value for activation gap

Fractional quantum Hall effect



Volume 48, Number 22 PHYSICAL REVIEW LETTERS 31 May 1982

Two-Dimensional Magnetotransport in the Extreme Quantum Limit

D. C. Tsui,[a],[b] H. L. Stormer,[a] and A. C. Gossard
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 5 March 1982)

A quantized Hall plateau of $\rho_{xy}=3h/e^2$, accompanied by a minimum in ρ_{xx}, was observed at $T<5$ K in magnetotransport of high-mobility, two-dimensional electrons, when the lowest-energy, spin-polarized Landau level is $\frac{1}{3}$ filled. The formation of a Wigner solid or charge-density-wave state with triangular symmetry is suggested as a possible explanation.

Seen in GaAs quantum well with electron mobility of 90,000 cm^2/V sec

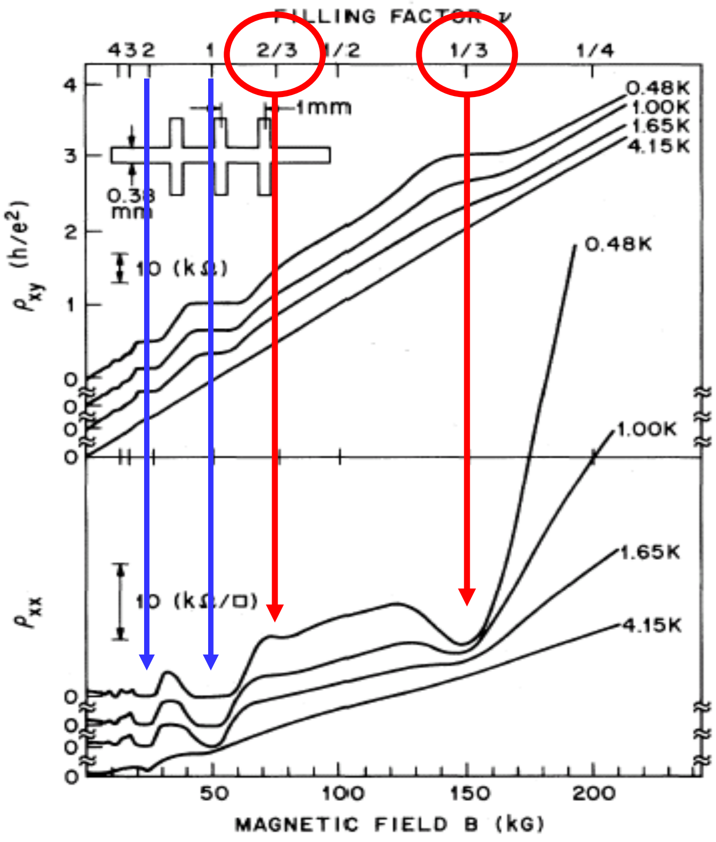
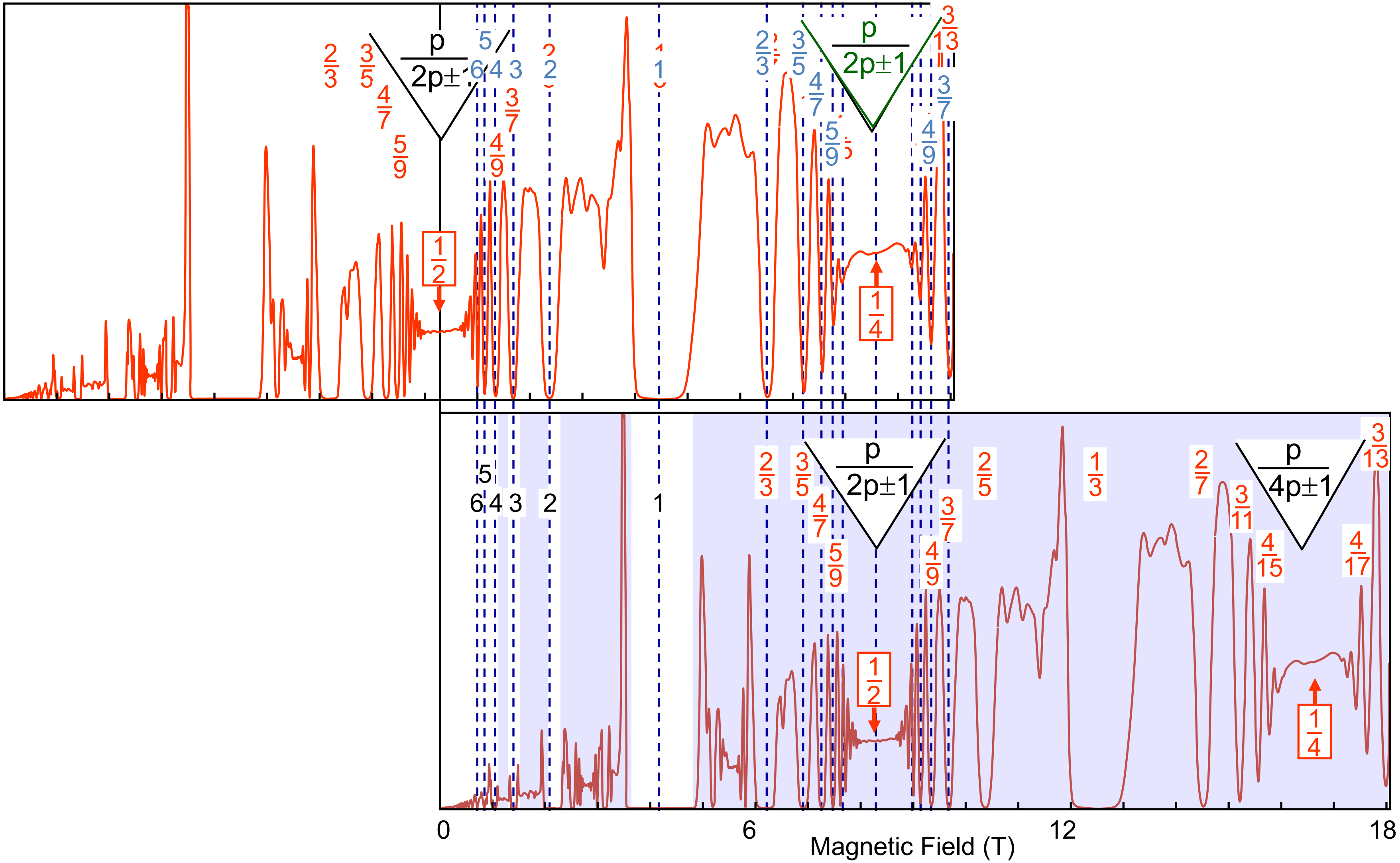


FIG. 1. ρ_{xy} and ρ_{xx} vs B, taken from a GaAs-Al$_{0.3}$-Ga$_{0.7}$As sample with $n=1.23\times10^{11}/\mathrm{cm}^2$, $\mu=90\,000\ \mathrm{cm}^2/$V sec, using $I=1\ \mu$A. The Landau level filling factor is defined by $\nu=nh/eB$.

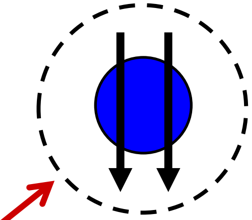
- Only started to show up in samples as quality increased
- Derives from electron-electron interaction (See Laughlin, Rev. Mod. Phys. 71, 863 (1999)

Fractional quantum Hall effect



Fractional quantum Hall effect

Theorists (Buckley Prize 2002) account for these facts by proposing a new particle called a composite-fermion consisting of an electron bound to 2 magnetic flux quanta.

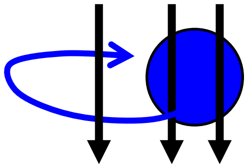


New particle

The composite-fermion removes from consideration the B-flux tied up in it's creation.

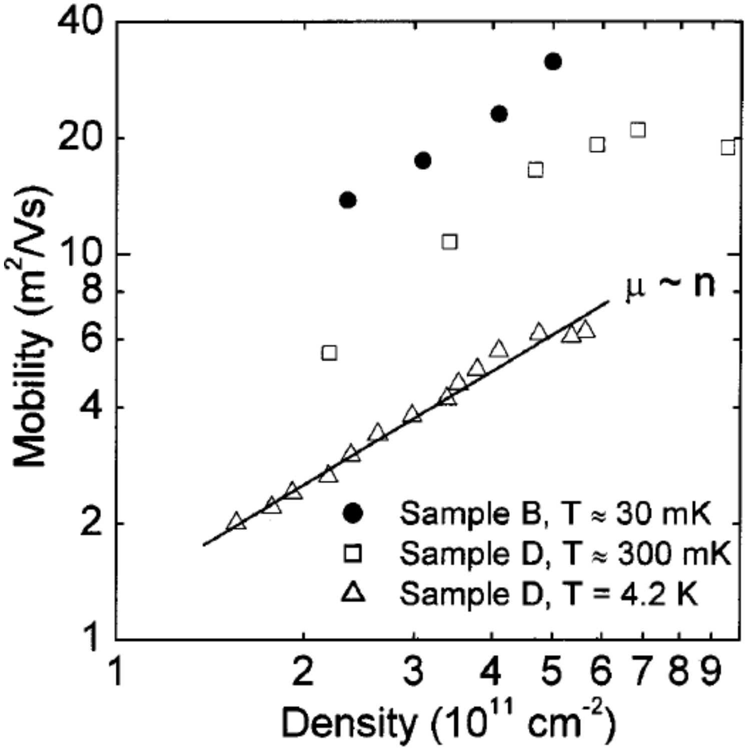
Thus the picture is changed to a set of composite-fermions in a B-field of much smaller value.

Picture of $v = 1/3$ FQH state



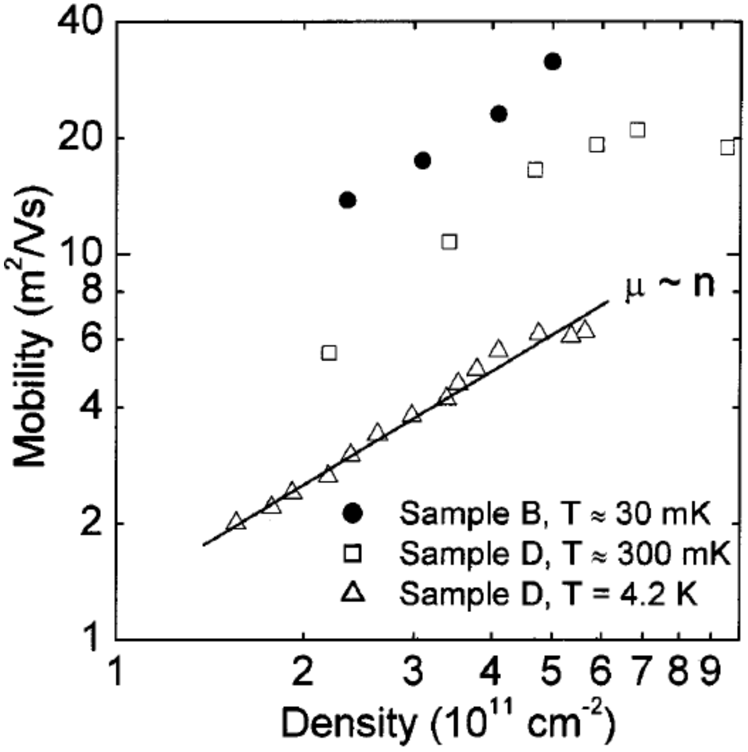
- The formation of these particles require high quality (even more for 4, 6 flux)
- Analogous to integer quantum Hall, just with quasiparticle, so same argument for high-quality indicators

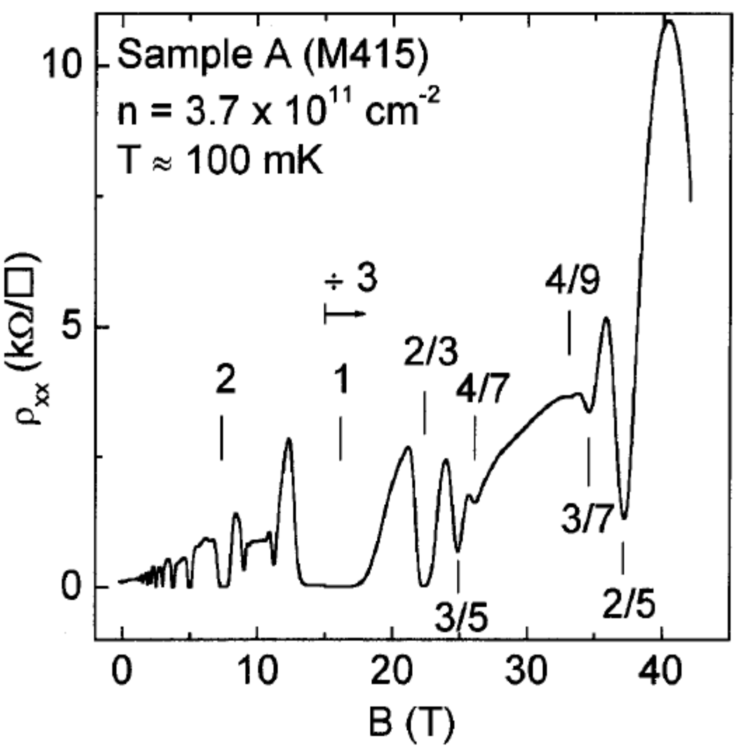
Status of AlAs 2DESs



E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

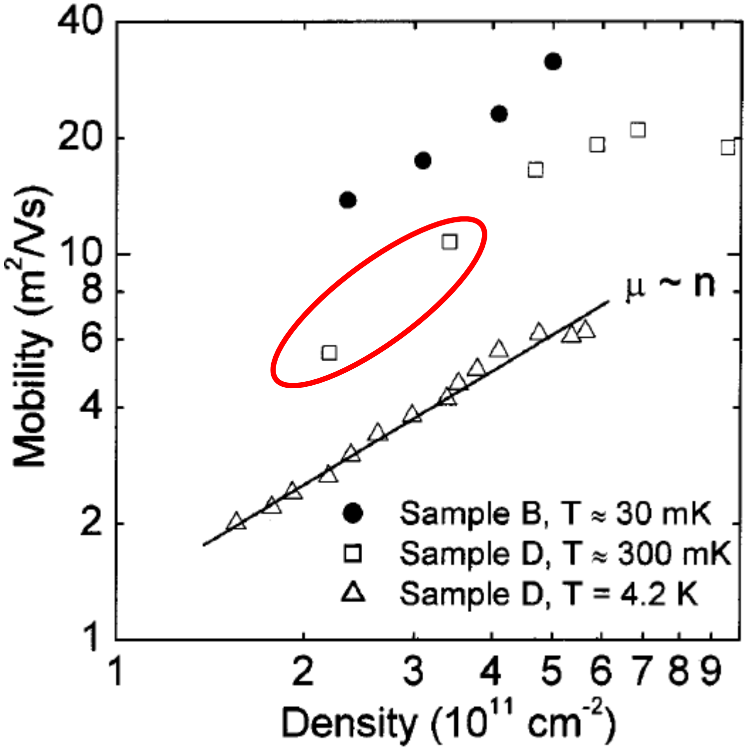
Status of AlAs 2DESs



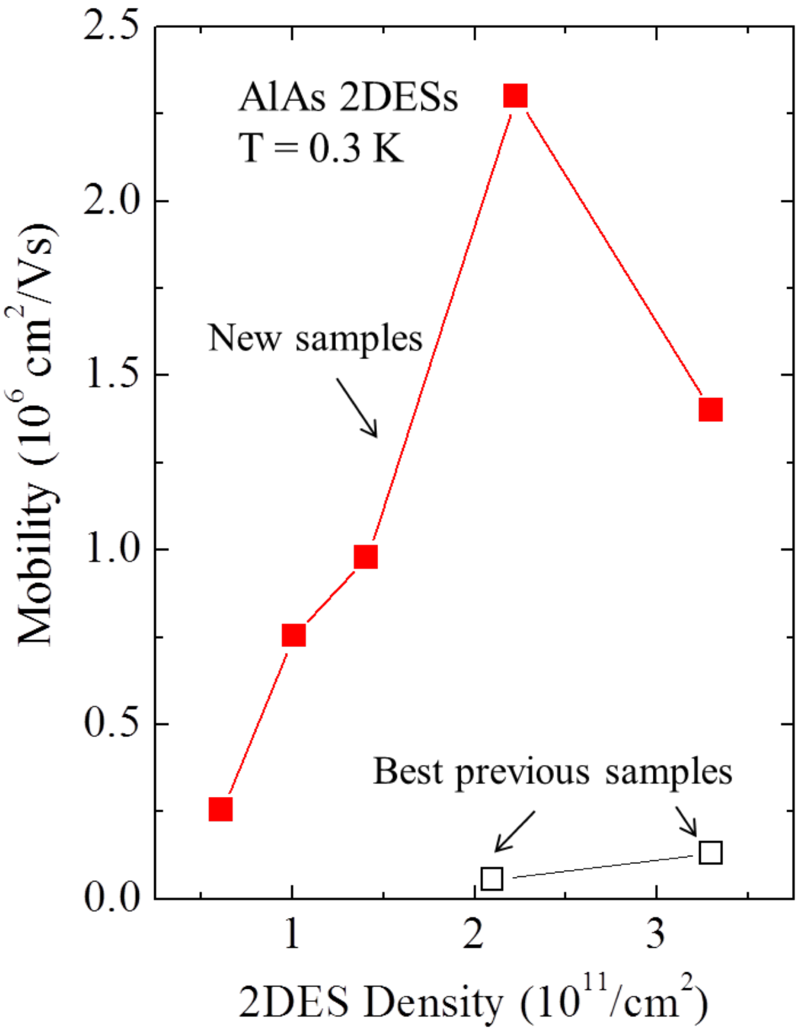


E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

Status of AlAs 2DESs

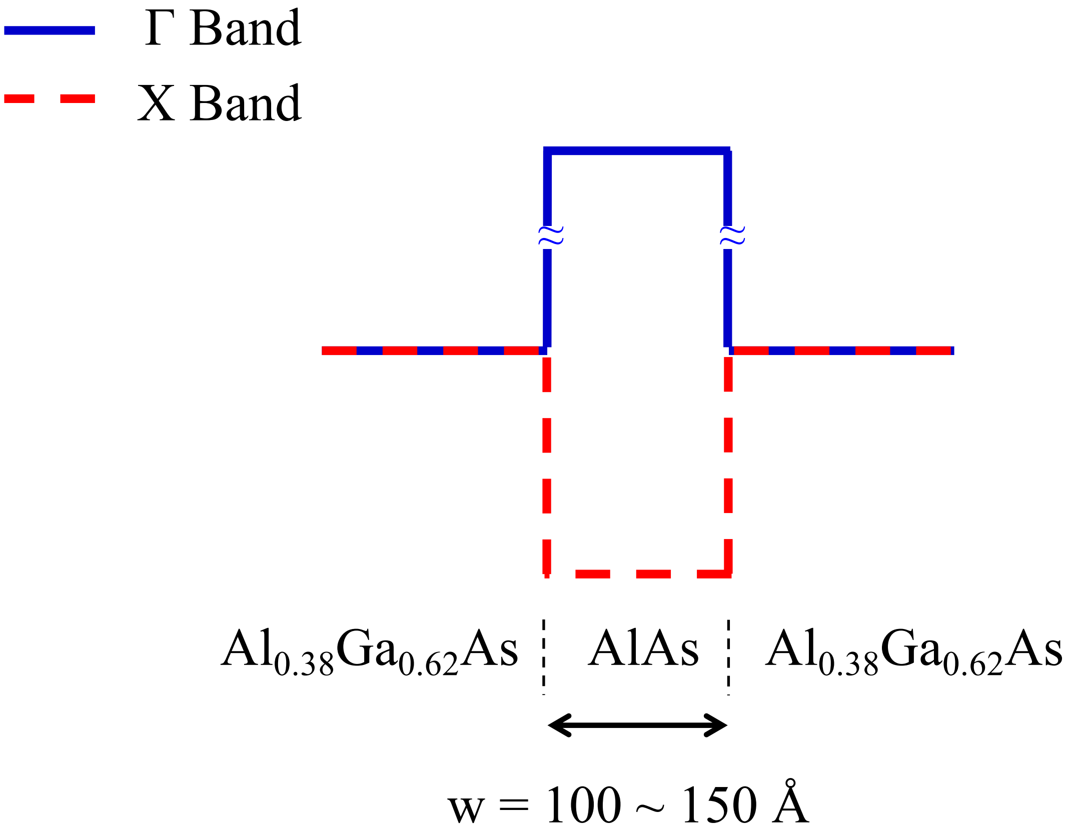


E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)



- Purification of Al source
- Well width optimization of the AlAs quantum well

The role of quantum well width



Γ Band

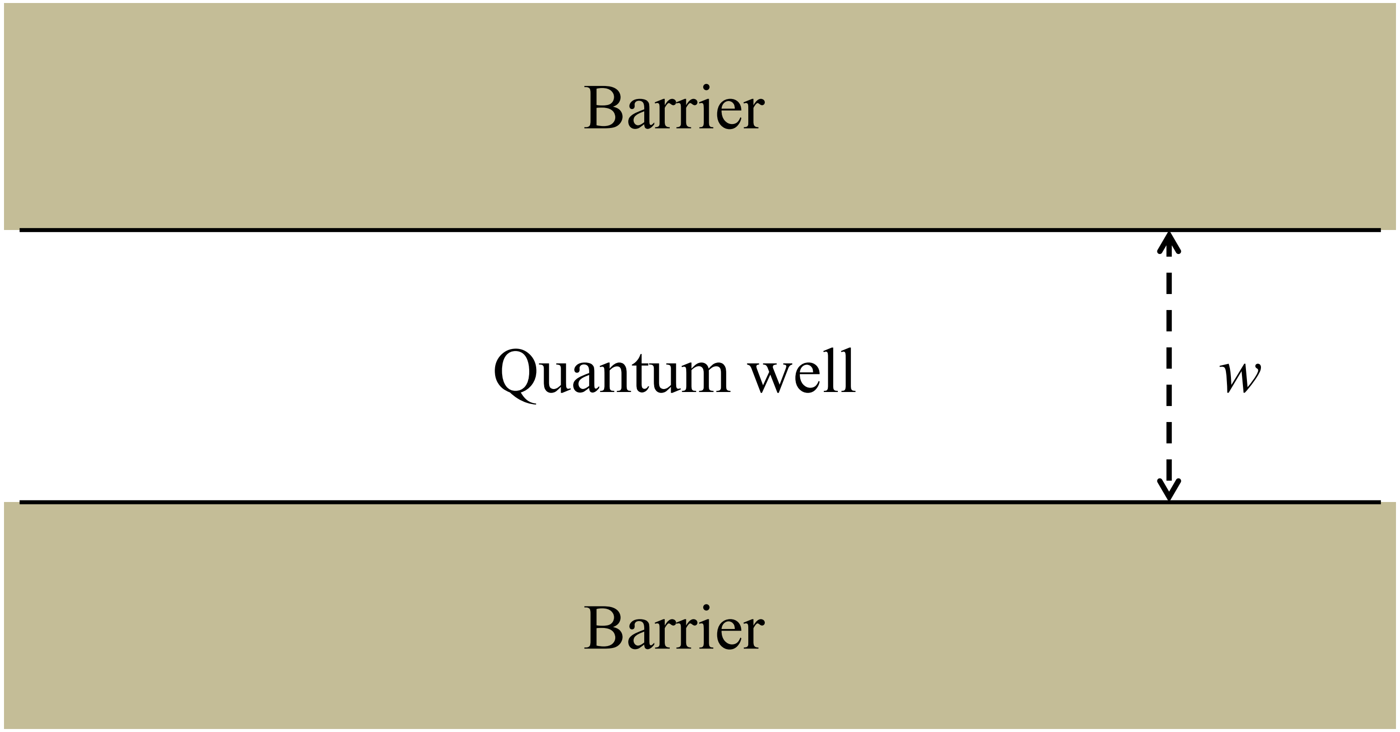
X Band

$Al_{0.38}Ga_{0.62}As$ AlAs $Al_{0.38}Ga_{0.62}As$

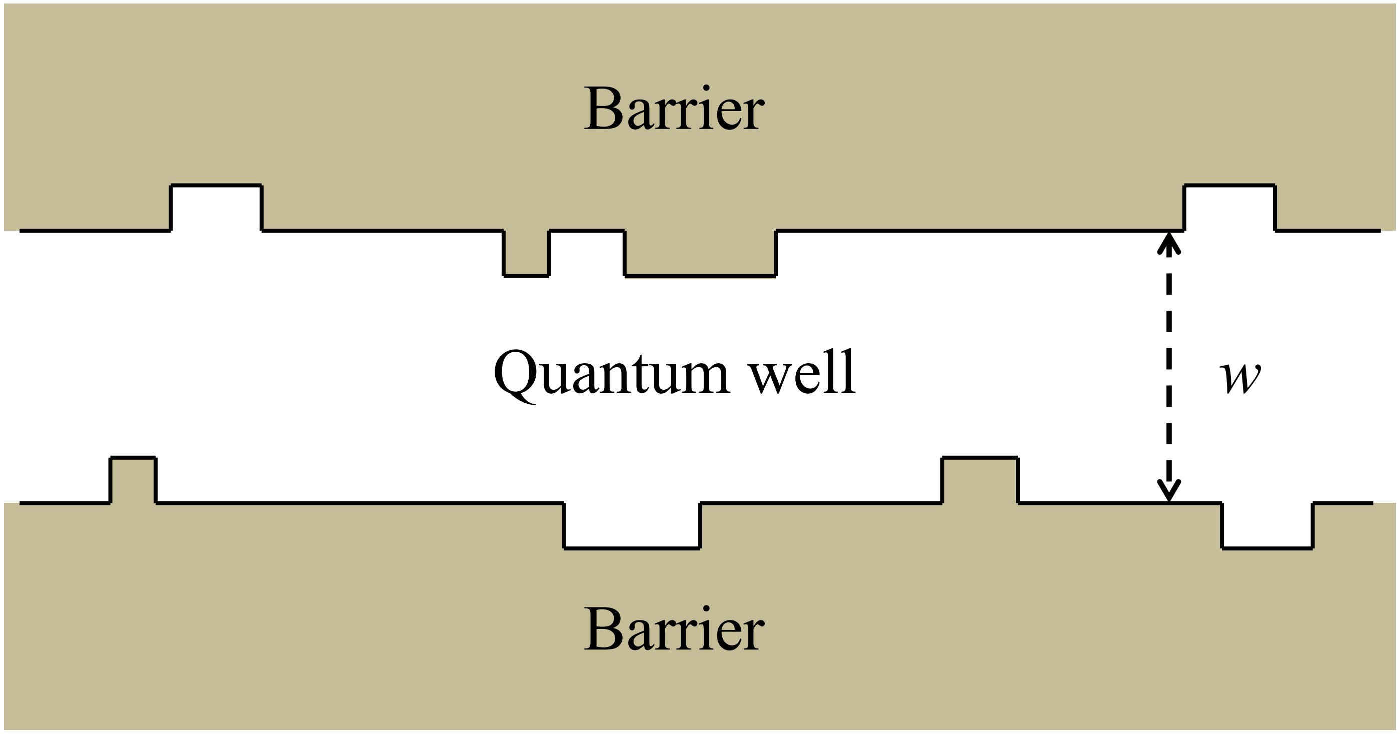
w = 100 ~ 150 Å

E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

The role of quantum well width

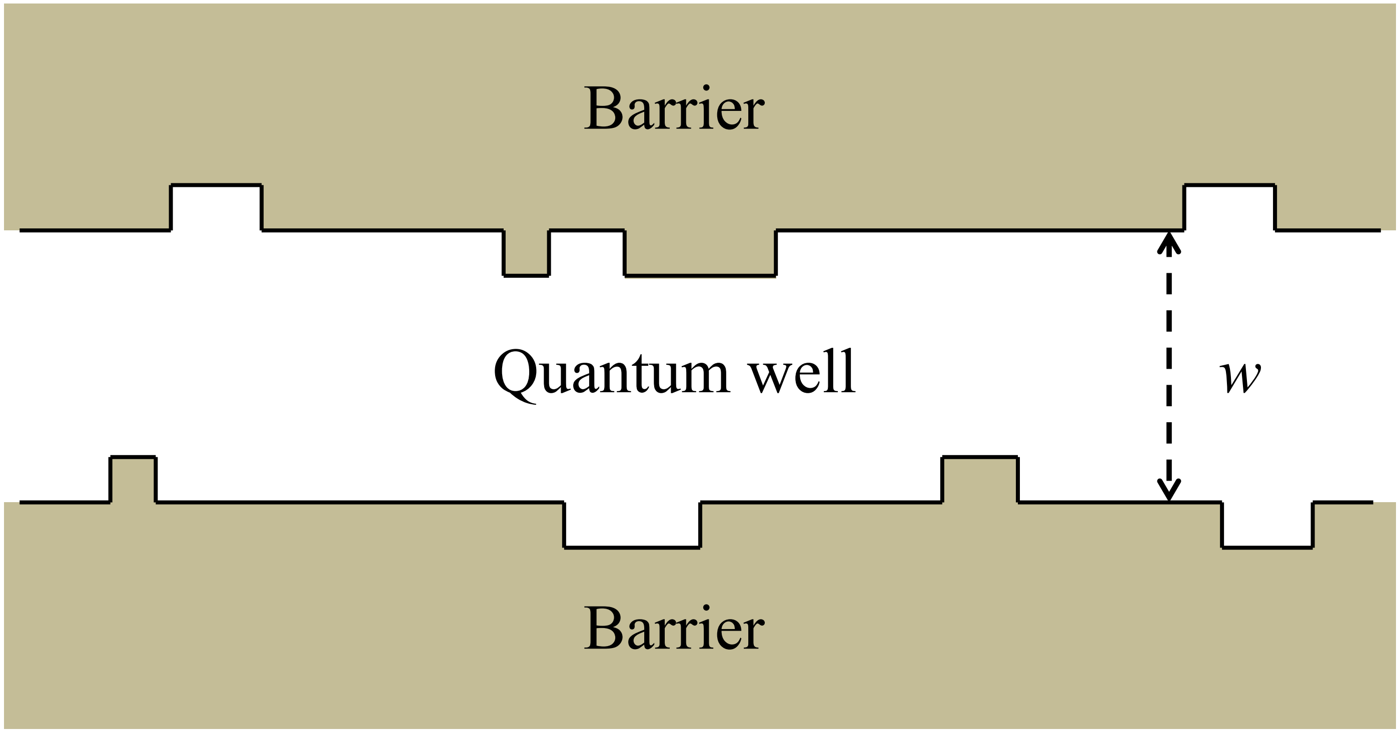


The role of quantum well width



Monolayer fluctuations (~ 2.8 Å in GaAs, AlAs)

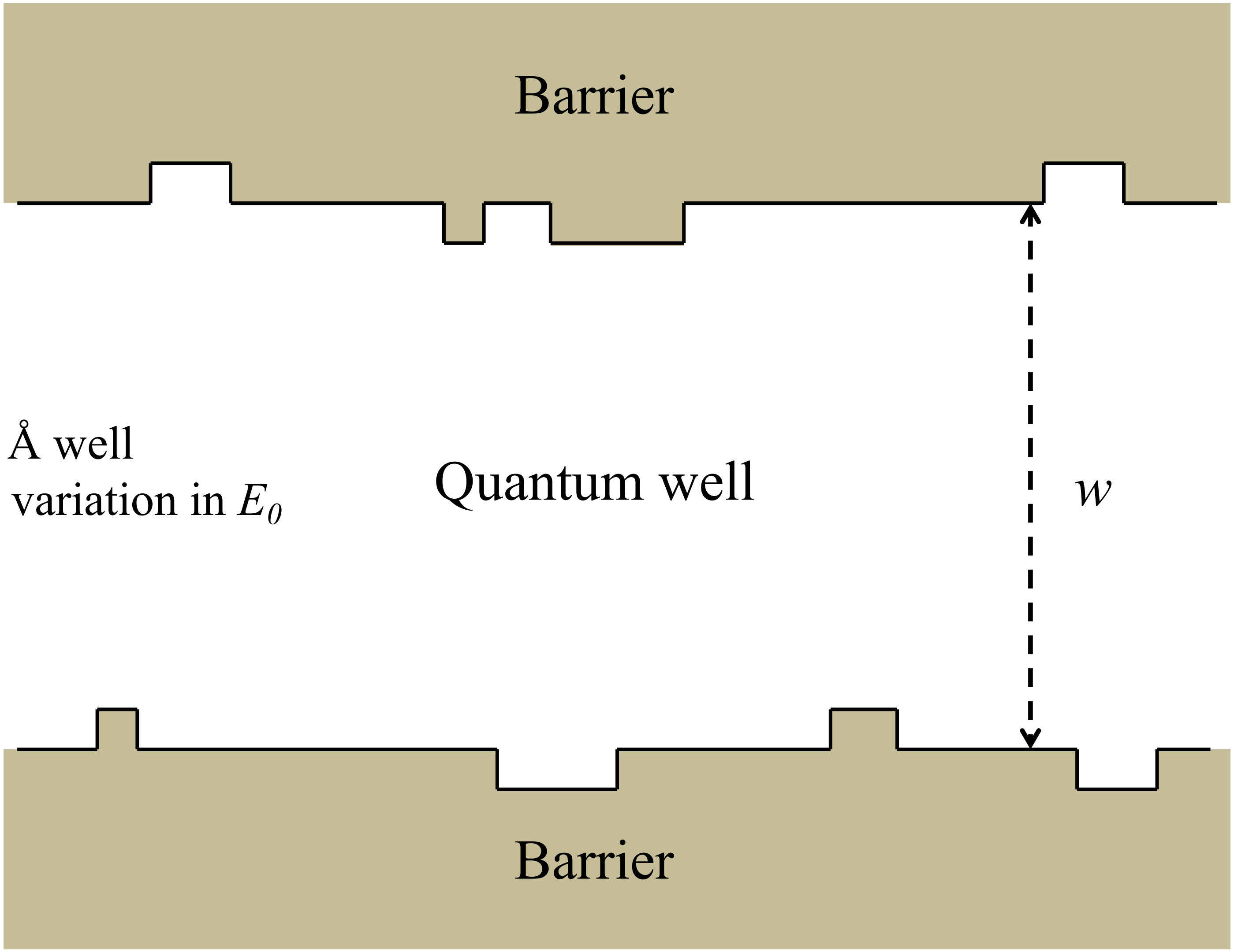
The role of quantum well width



Monolayer fluctuations (~ 2.8 Å in GaAs, AlAs)

$$E_0 = \frac{\pi^2 \hbar^2}{2mw^2}$$ ➡ Therefore, for ~ 100 Å well, ~ 6 % variation in E_0

The role of quantum well width



Barrier

Quantum well

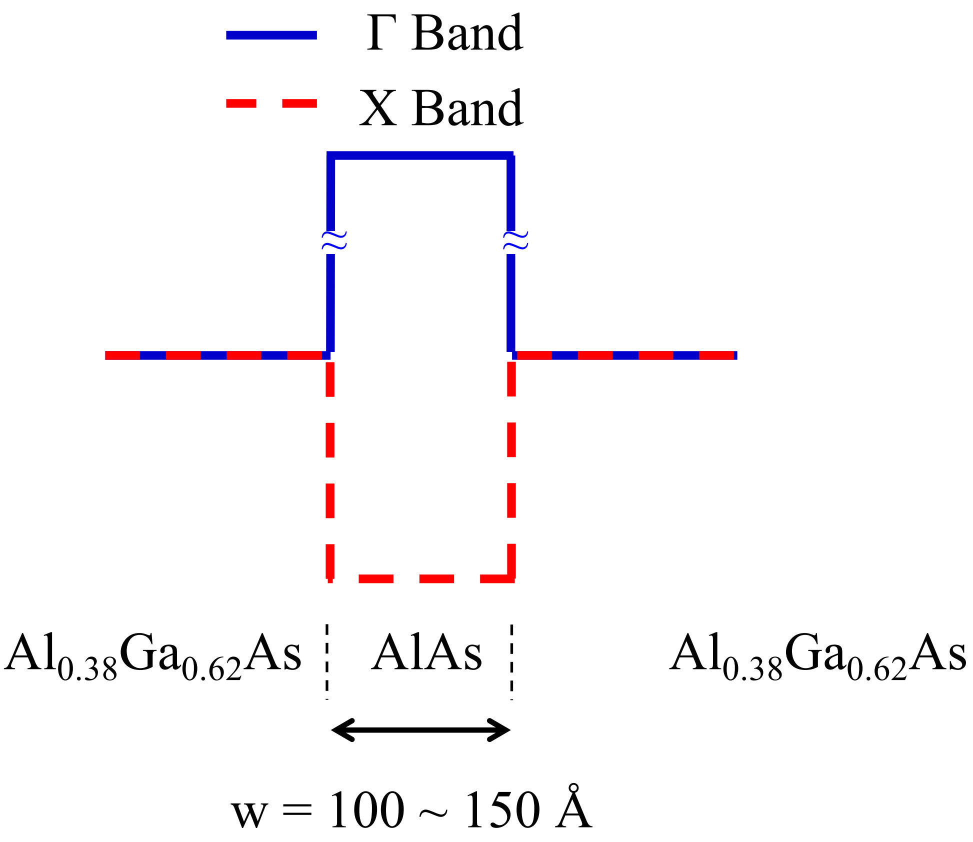
w

Barrier

~ 300 Å well

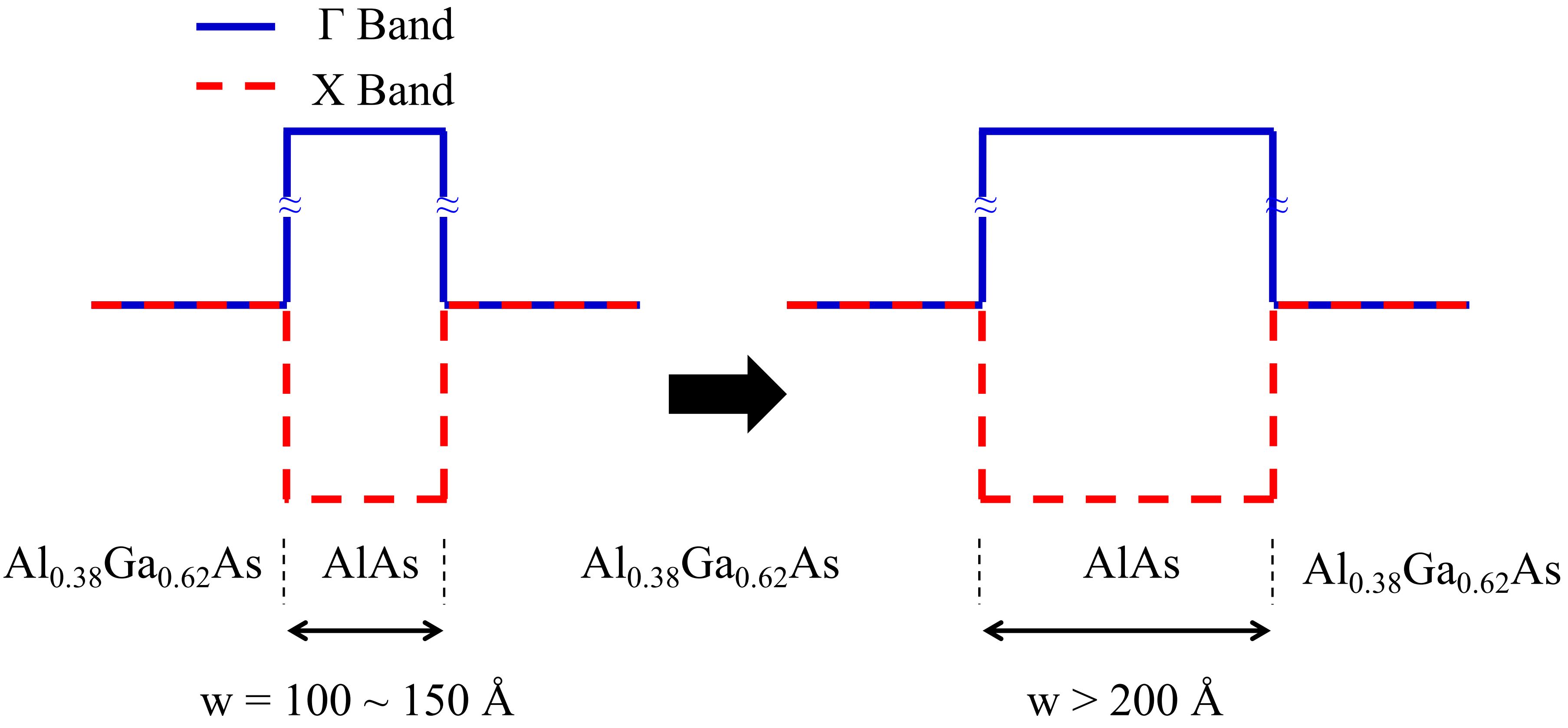
~ 2 % variation in E_0

The role of quantum well width



E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

The role of quantum well width



Γ Band

X Band

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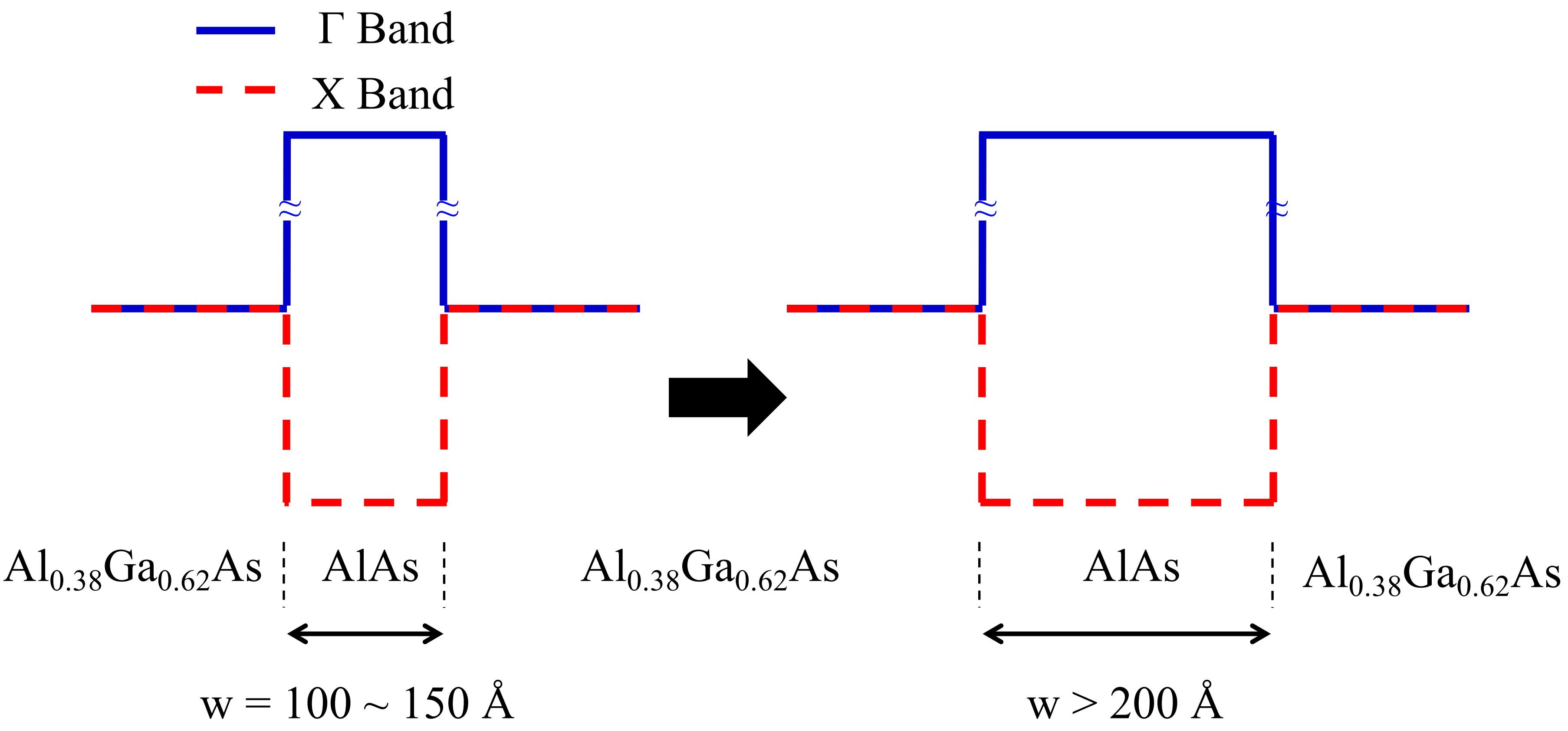
w = 100 ~ 150 Å

$Al_{0.38}Ga_{0.62}As$ AlAs $Al_{0.38}Ga_{0.62}As$

w > 200 Å

E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

The role of quantum well width



Γ Band

X Band

$Al_{0.38}Ga_{0.62}As$ AlAs $Al_{0.38}Ga_{0.62}As$

w = 100 ~ 150 Å

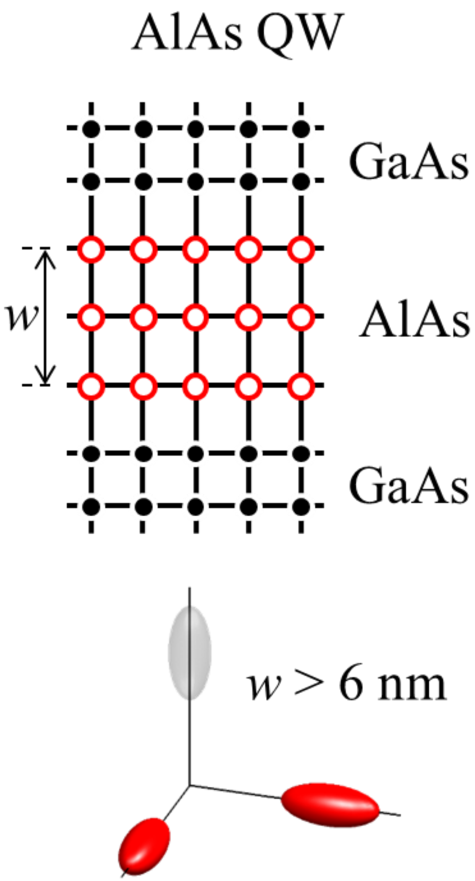
AlAs $Al_{0.38}Ga_{0.62}As$

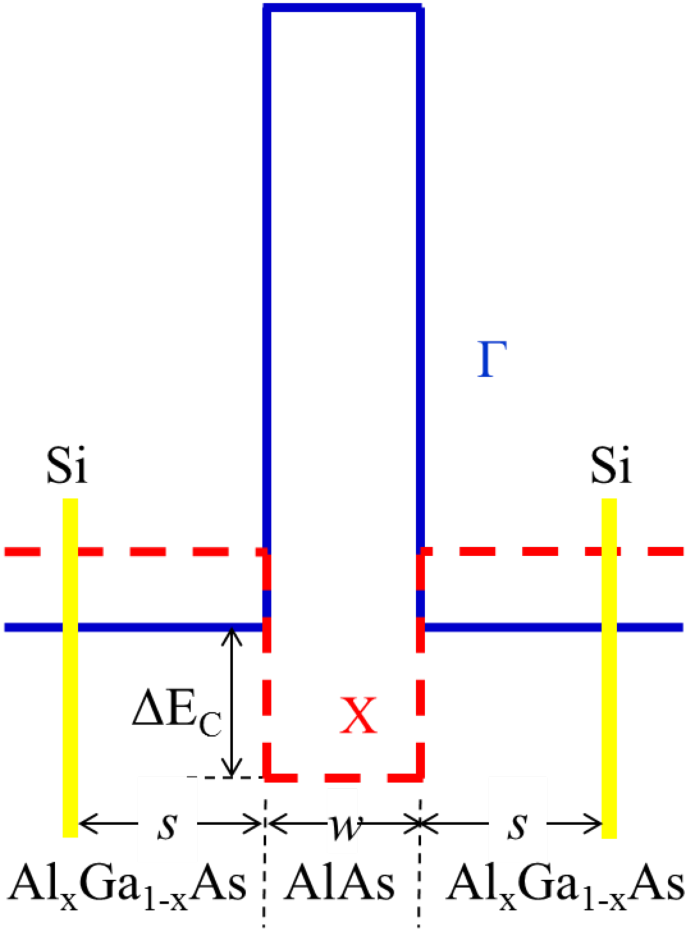
w > 200 Å

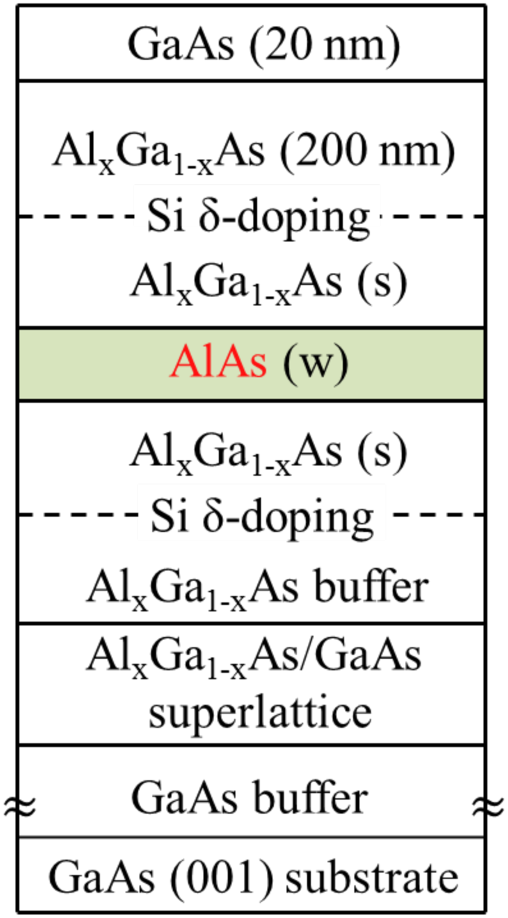
Not so trivial! Requires high-purity Al source

E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

Sample structure for record-quality AlAs 2DESs







GaAs (20 nm)

$Al_xGa_{1-x}As$ (200 nm)

Si δ-doping

$Al_xGa_{1-x}As$ (s)

AlAs (w)

$Al_xGa_{1-x}As$ (s)

Si δ-doping

$Al_xGa_{1-x}As$ buffer

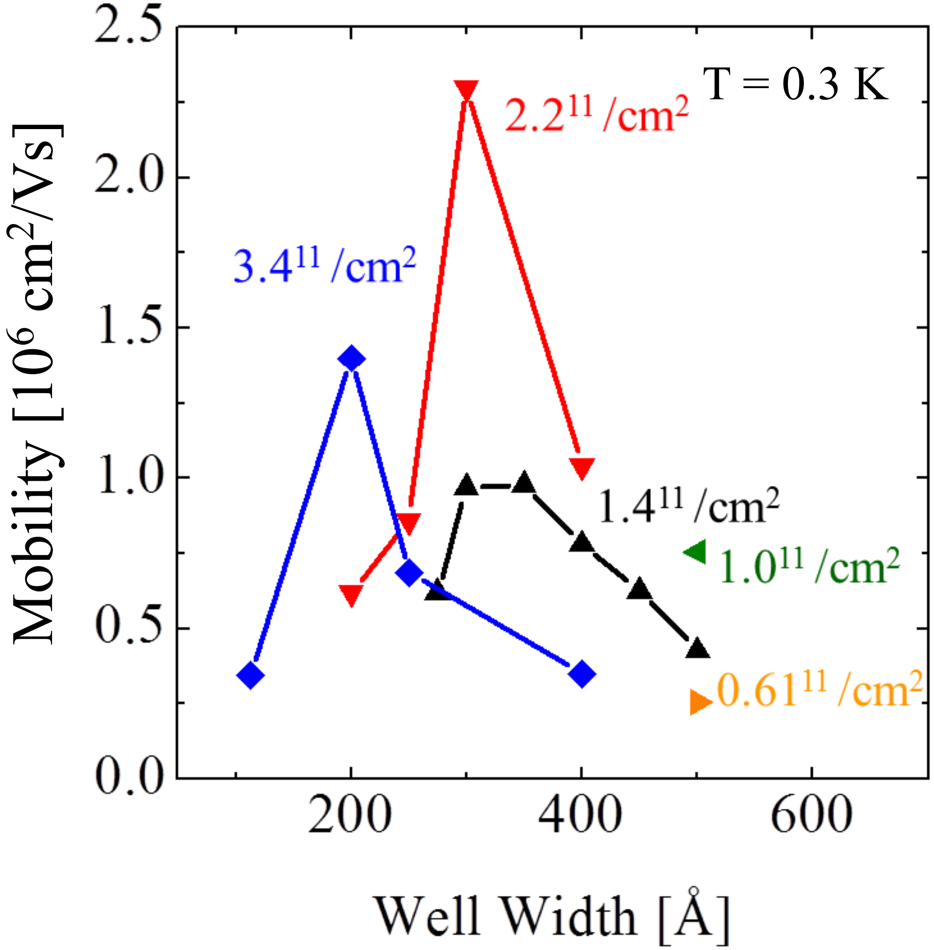
$Al_xGa_{1-x}As$/GaAs superlattice

GaAs buffer

GaAs (001) substrate

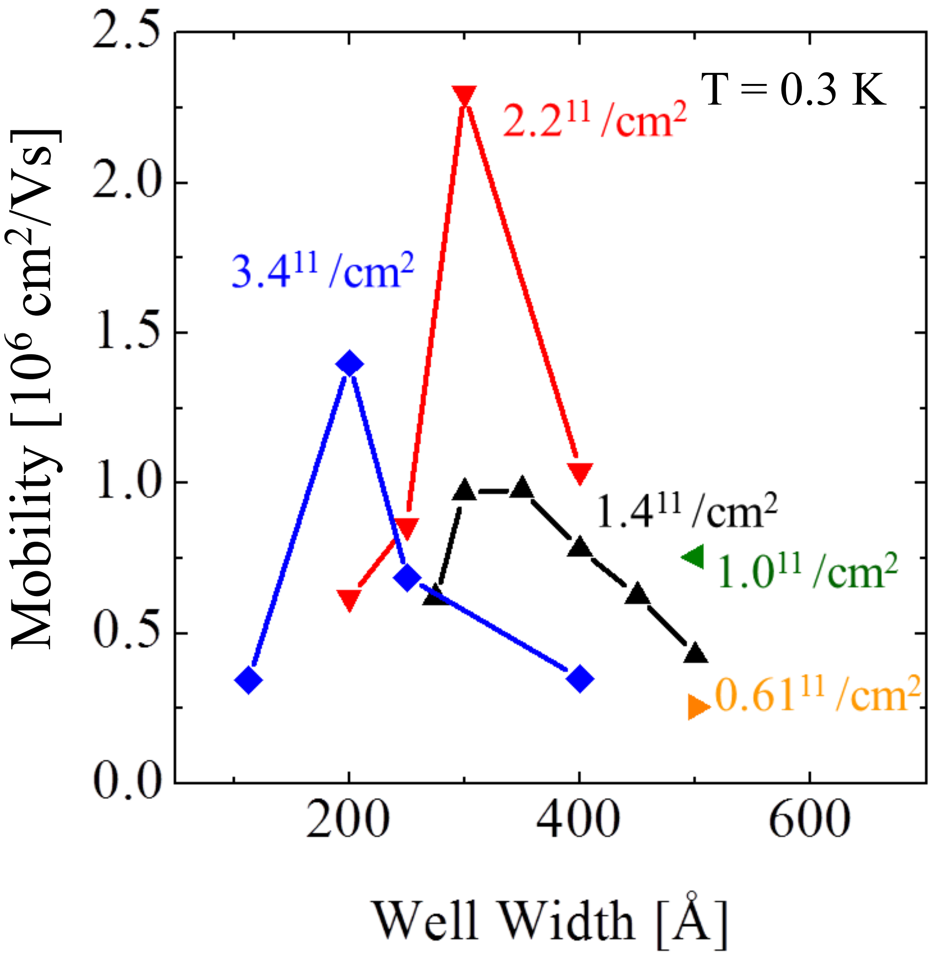
Y. J. Chung, Phys. Rev. Mater. **2**, 071001(R) (2018)

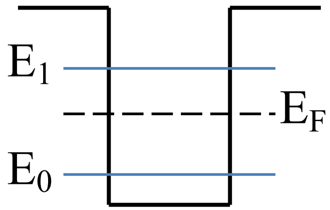
Mobility vs AlAs well width

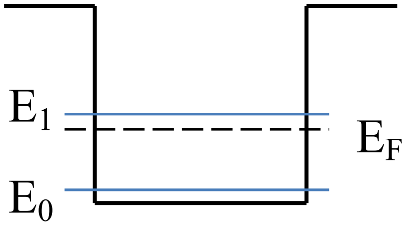


- We are now able to grow very wide AlAs quantum wells
- Wide AlAs have order of magnitude higher μ than 'narrow' wells

Mobility vs AlAs well width







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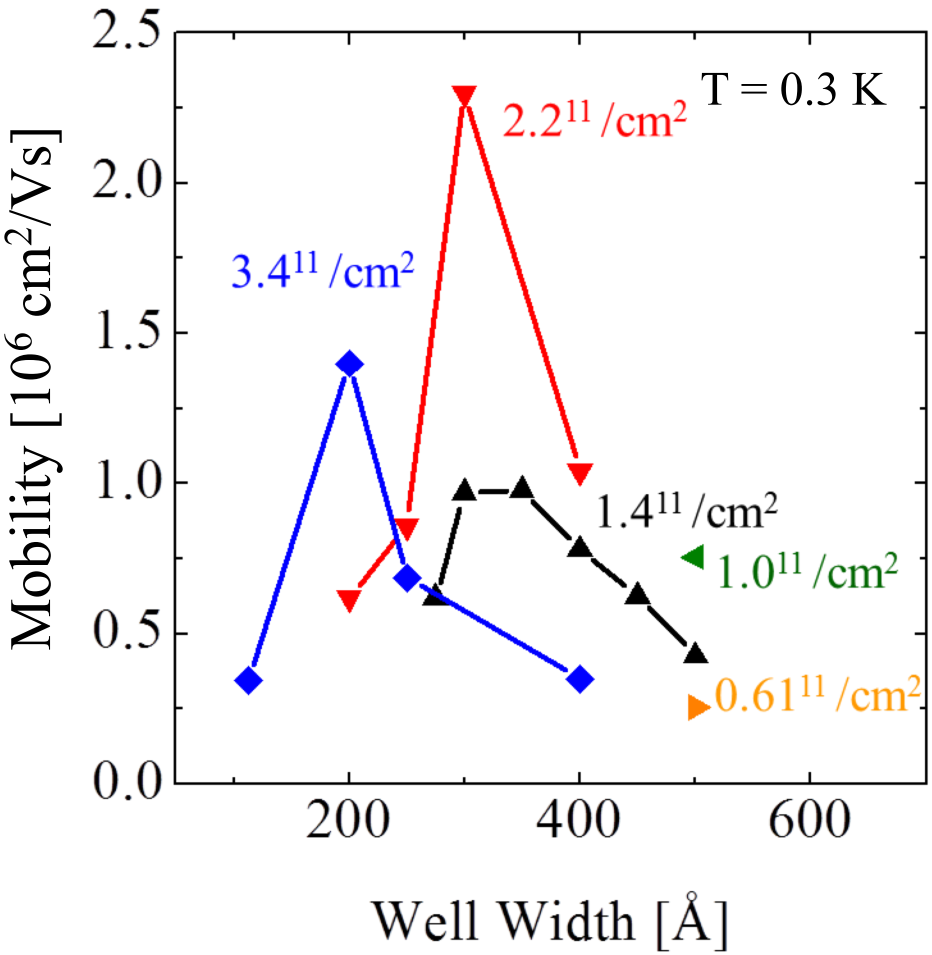
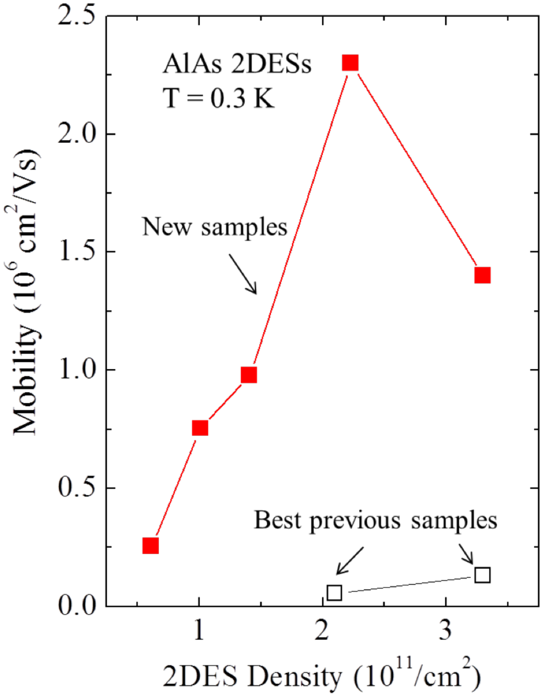
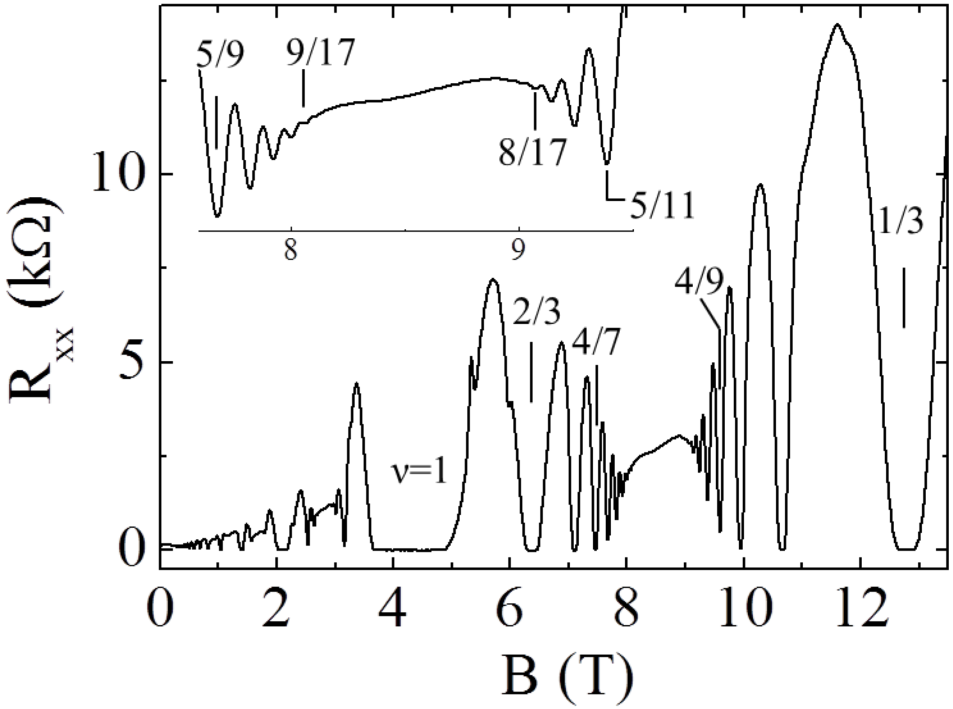
Mobility vs AlAs well width





- We are now able to grow very wide AlAs quantum wells
- Wide AlAs have order of magnitude higher μ than ‘narrow’ wells

Magnetotransport of record-quality AlAs 2DESs



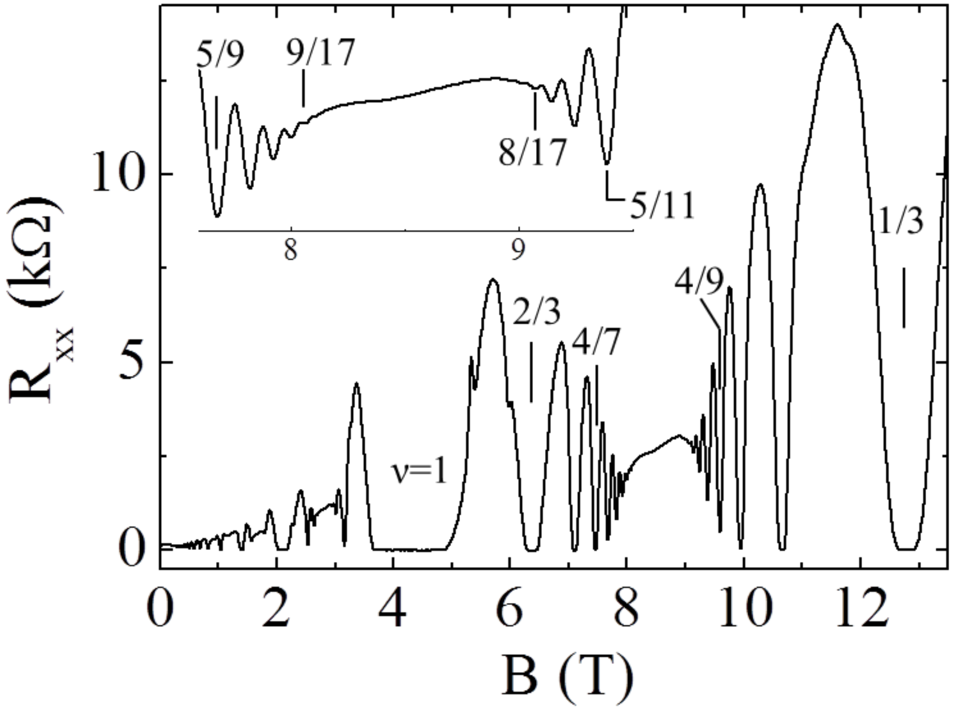
T = 100 mK

n = 1.0 x 10^{11} /cm^2

μ = 753,000 cm^2/Vs

Unprecedented quality!

Magnetotransport of record-quality AlAs 2DESs



T = 100 mK
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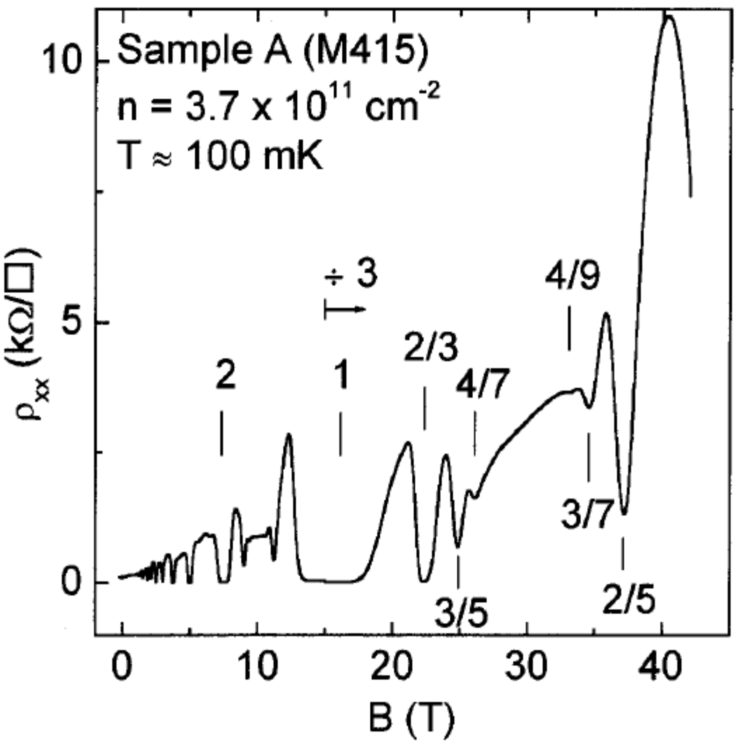
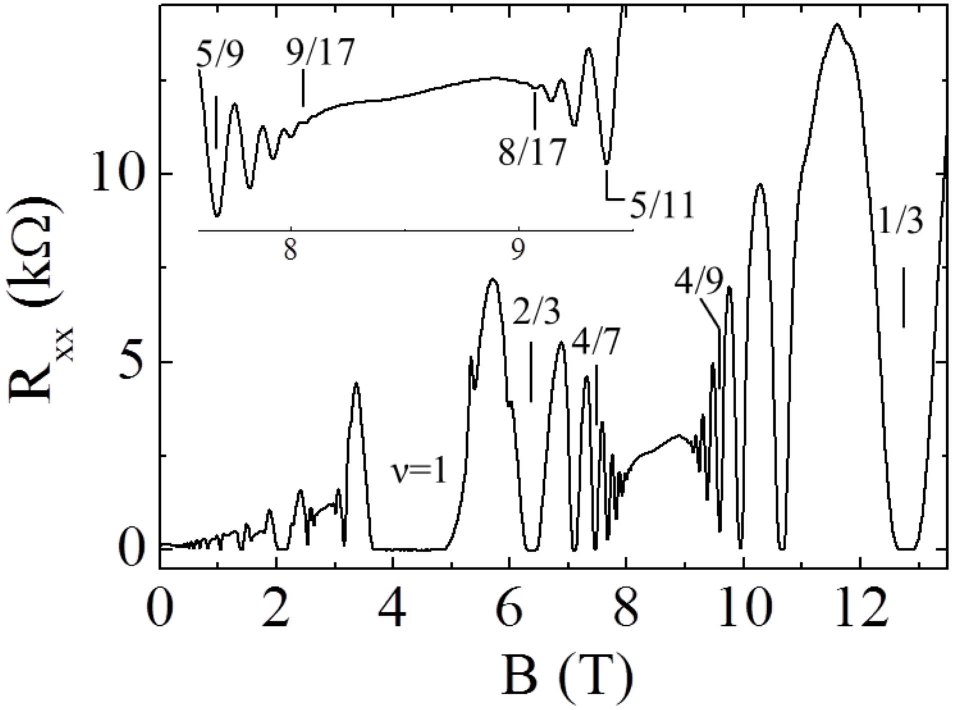
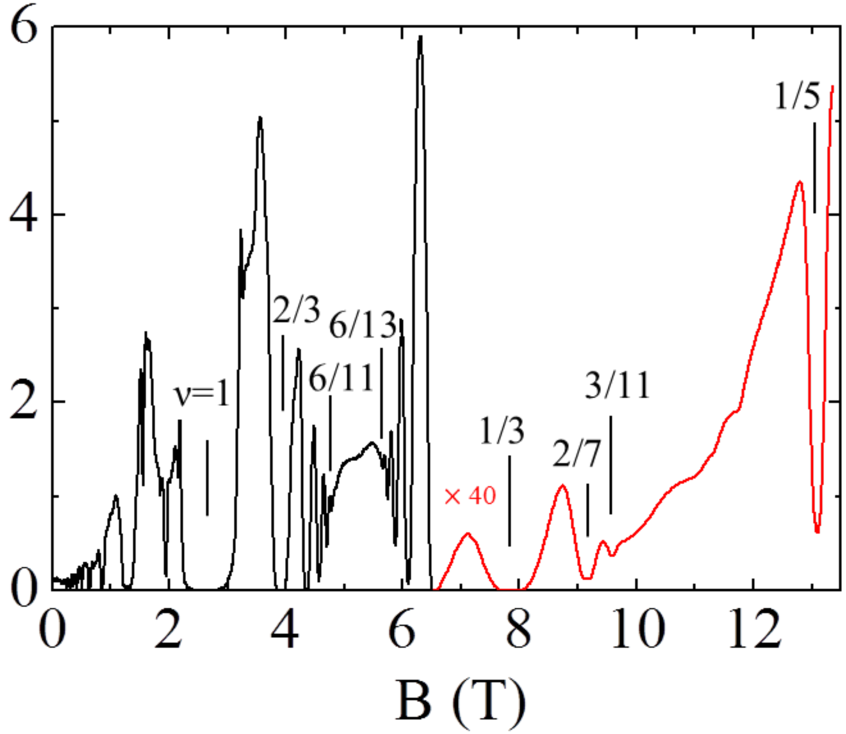


E. de Poortere, Appl. Phys. Lett. **80** 1583 (2002)

Unprecedented quality!

Magnetotransport of record-quality AlAs 2DESs





T = 100 mK
n = 1.0 x 10^{11} /cm^2
μ = 753,000 cm^2/Vs

T = 100 mK
n = 6.1 x 10^{10} /cm^2
μ = 253,000 cm^2/Vs

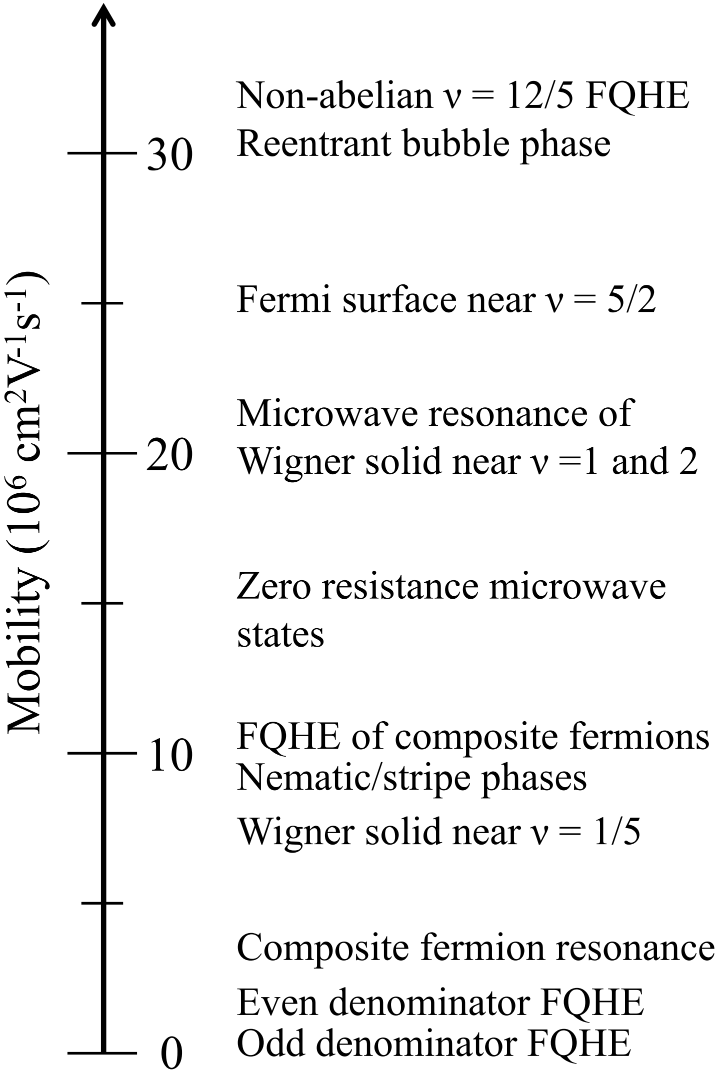
Unprecedented quality!

Y. J. Chung, Phys. Rev. Mater. **2**, 071001(R) (2018)

Outline

- Introduction
  - Clean 2DESs and the GaAs/AlAs materials group
- 2DESs in GaAs/AlAs quantum wells
  - Defining GaAs and AlAs 2DESs
  - Systematic impurity reduction
  - Record-quality AlAs and GaAs 2DESs
- Summary

Status of GaAs 2DESs



Non-abelian ν = 12/5 FQHE
Reentrant bubble phase

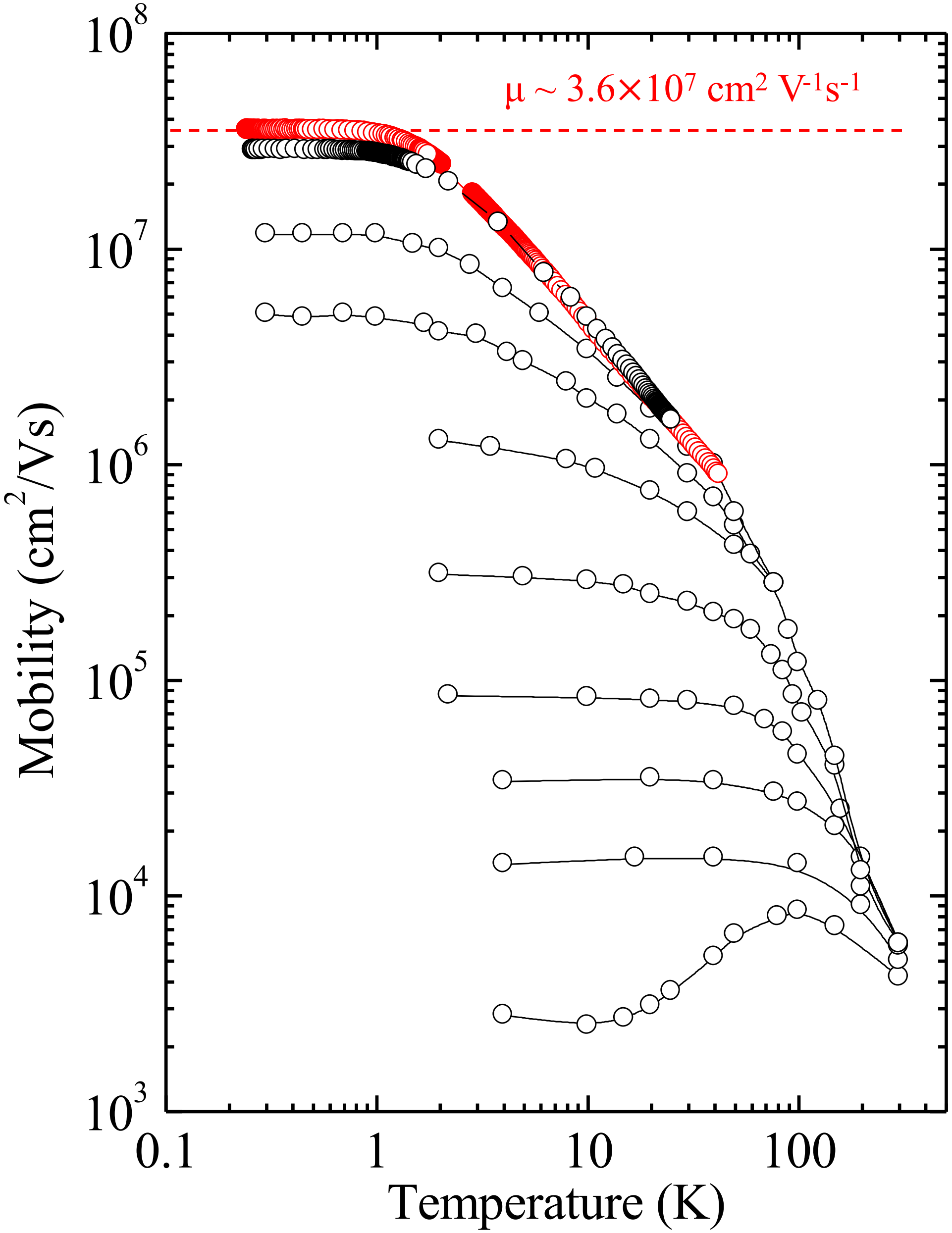
Fermi surface near ν = 5/2

Microwave resonance of
Wigner solid near ν =1 and 2

Zero resistance microwave
states

FQHE of composite fermions
Nematic/stripe phases
Wigner solid near ν = 1/5

Composite fermion resonance
Even denominator FQHE
Odd denominator FQHE



Status of GaAs 2DESs

What is limiting us from going higher?

Background impurities

E. H. Hwang, PRB 77, 235437 (2008)
S. D. Sarma, PRB 91, 205304 (2015)
M. Sammon, PRM 2, 064604 (2018)

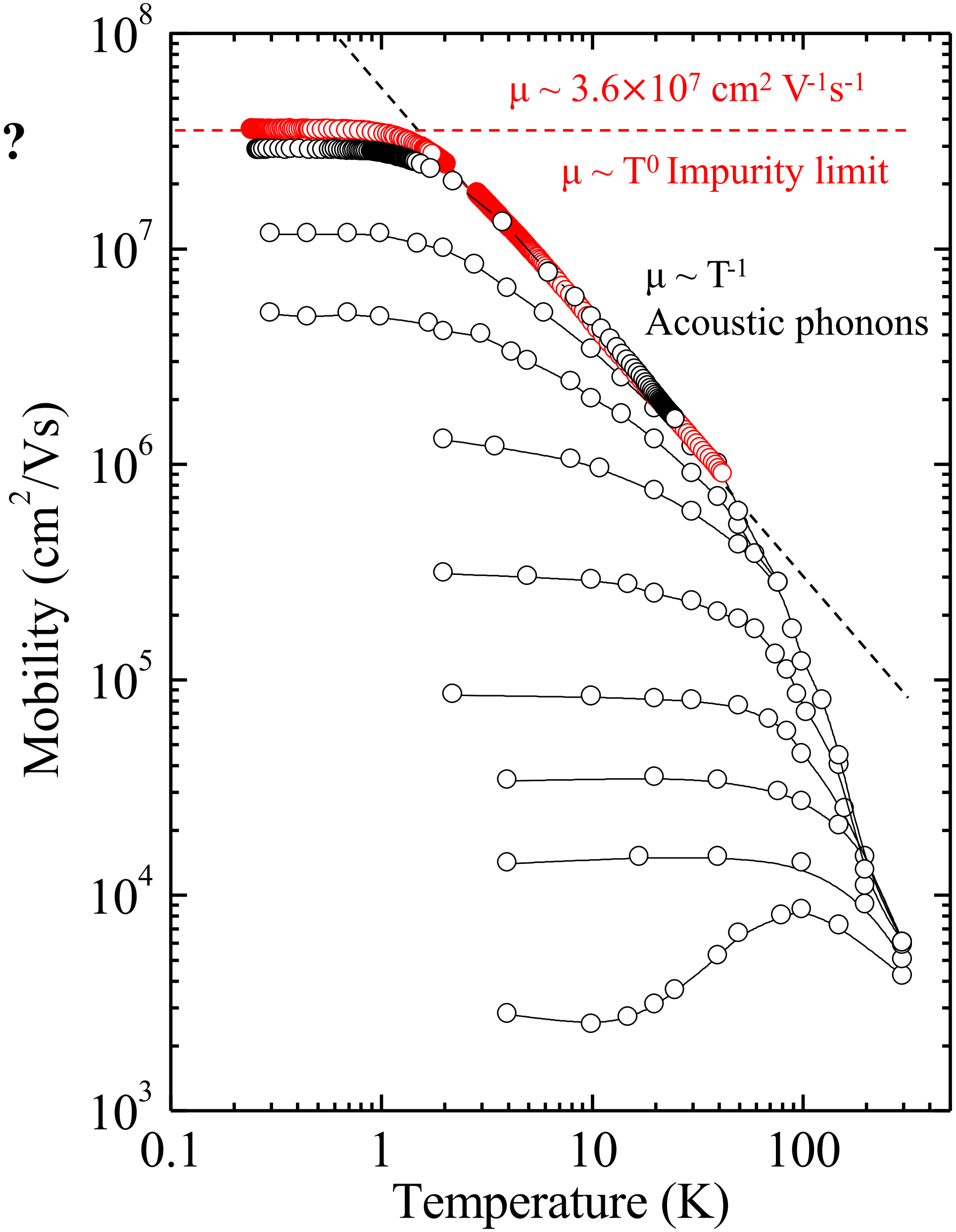
1. Source materials

G. C. Gardner, J. Cryst. G. 441, 71 (2016)
F. Schläpfer, J. Cryst. G. 442, 114 (2016)

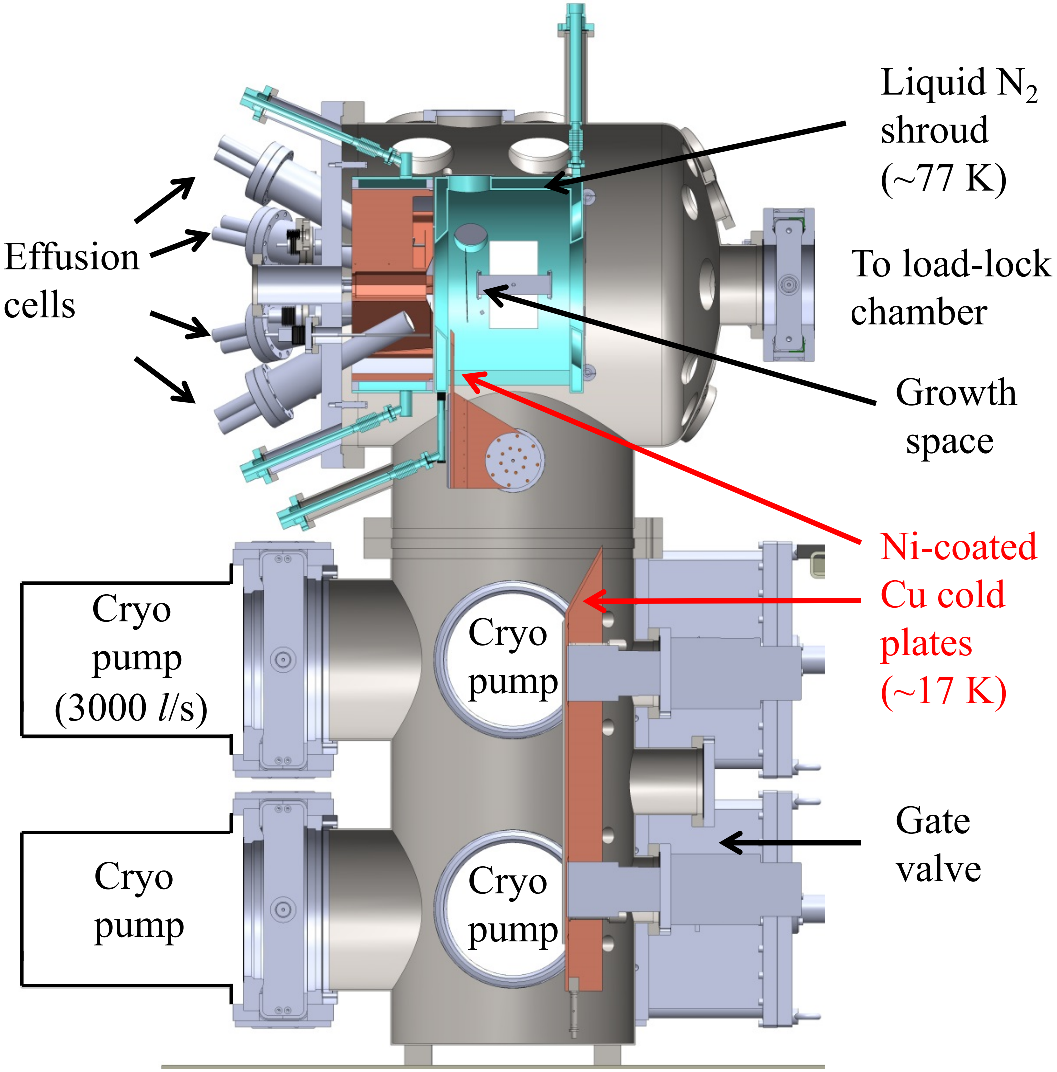
Y. J. Chung, PRM 2, 034006 (2018)

Still stuck!

2. Vacuum



Recap - cleaner growth environment



Liquid N_2 shroud (~77 K)

Effusion cells

To load-lock chamber

Growth space

Ni-coated Cu cold plates (~17 K)

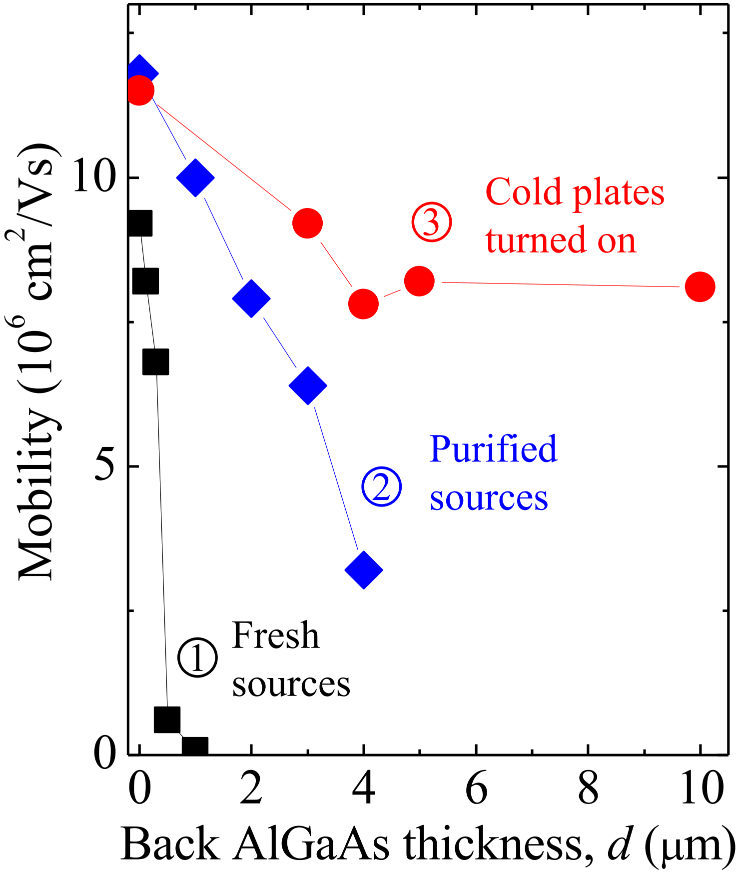
Cryo pump (3000 *l*/s)

Cryo pump

Cryo pump

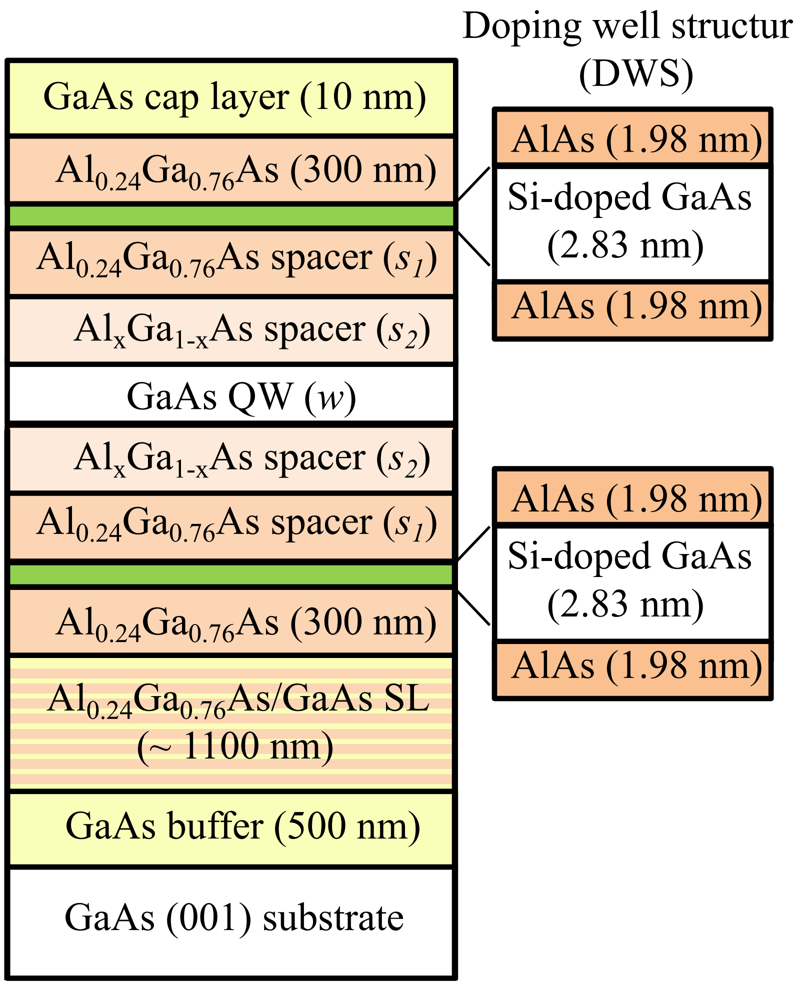
Cryo pump

Gate valve



Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Record-quality GaAs 2DESs



GaAs cap layer (10 nm)

$Al_{0.24}Ga_{0.76}As$ (300 nm)

$Al_{0.24}Ga_{0.76}As$ spacer (s_1)

$Al_xGa_{1-x}As$ spacer (s_2)

GaAs QW (w)

$Al_xGa_{1-x}As$ spacer (s_2)

$Al_{0.24}Ga_{0.76}As$ spacer (s_1)

$Al_{0.24}Ga_{0.76}As$ (300 nm)

$Al_{0.24}Ga_{0.76}As$/GaAs SL
(~ 1100 nm)

GaAs buffer (500 nm)

GaAs (001) substrate

Doping well structure
(DWS)

AlAs (1.98 nm)

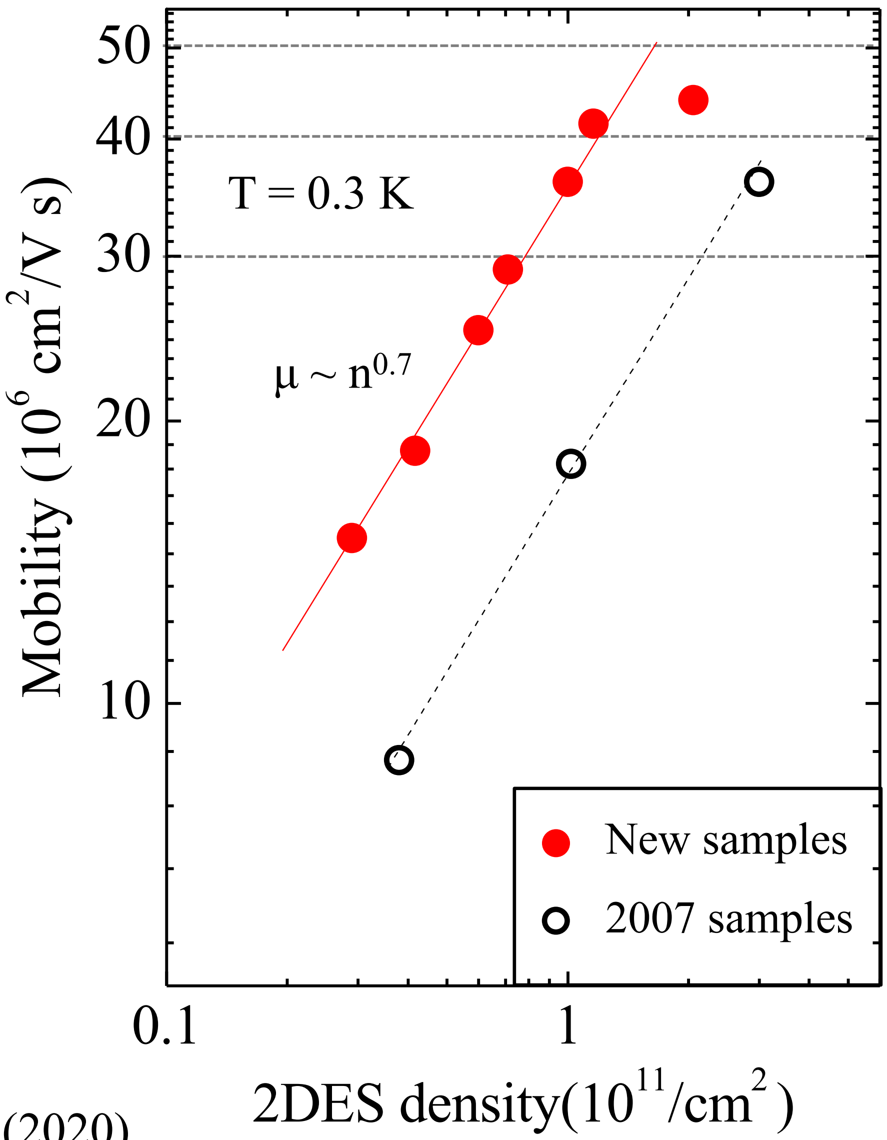
Si-doped GaAs
(2.83 nm)

AlAs (1.98 nm)

AlAs (1.98 nm)

Si-doped GaAs
(2.83 nm)

AlAs (1.98 nm)



Y. J. Chung, Phys. Rev. Mater. **4**, 044003 (2020)

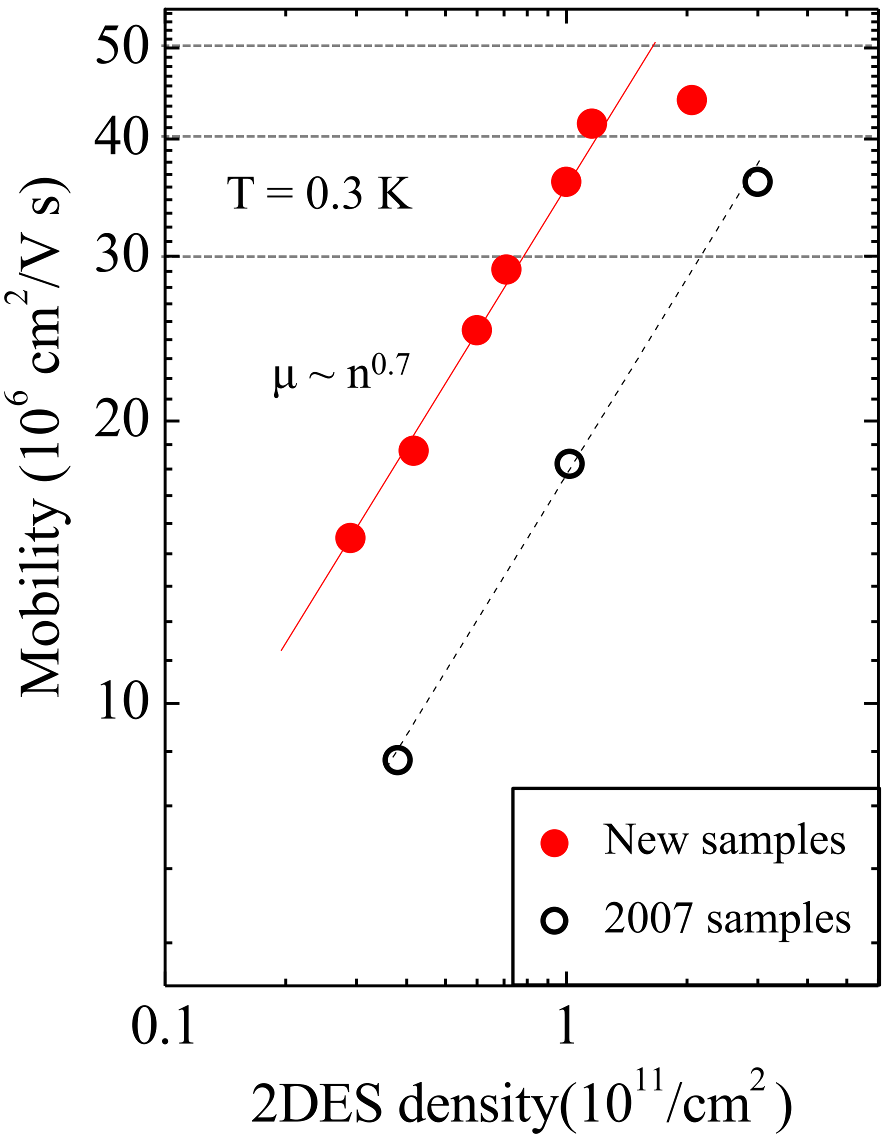
Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Record-quality GaAs 2DESs

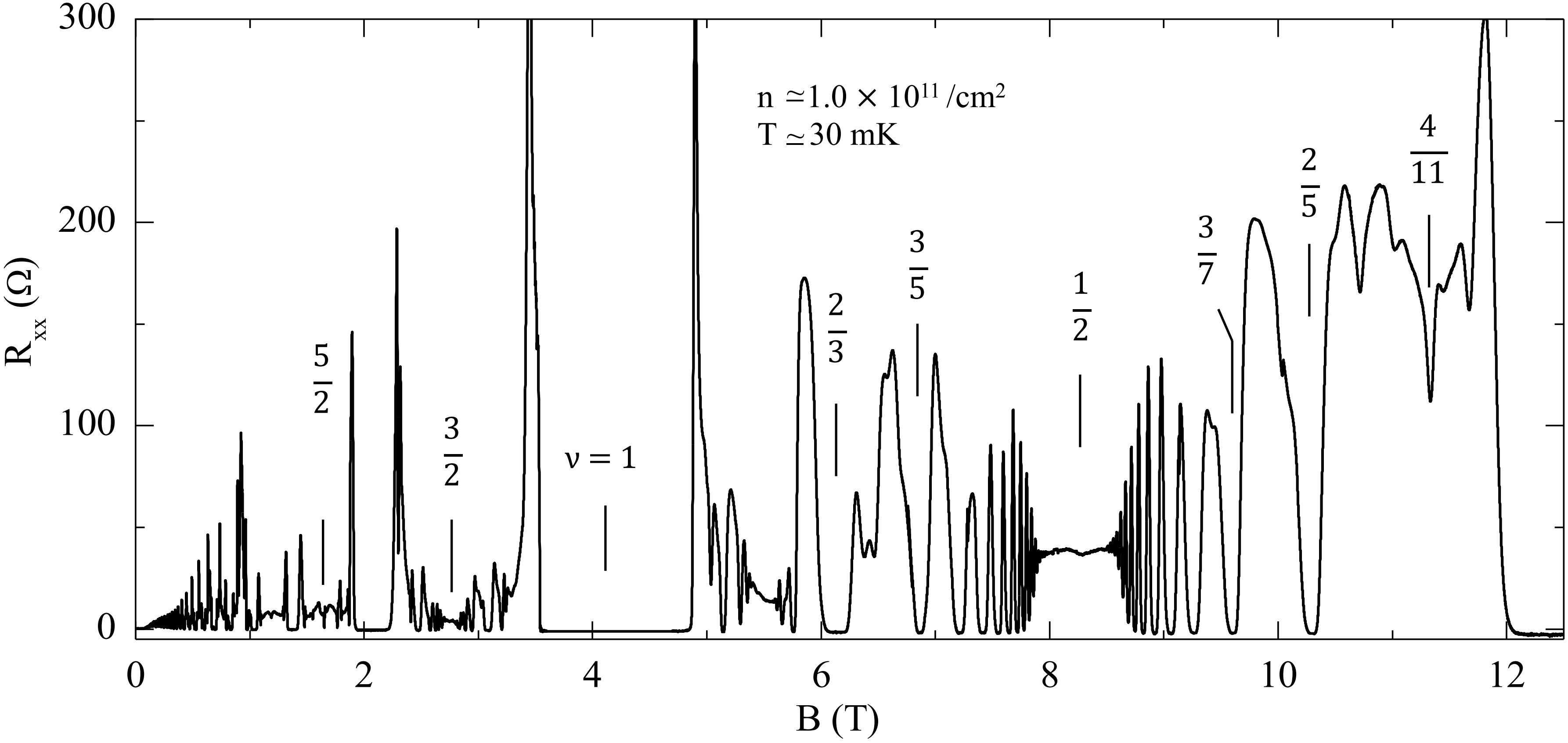
- **New world record for mobility!**
  $\mu \sim 4.4\times10^{7}$ cm^2/Vs at
  $n \sim 2\times10^{11}$ $/cm^2$

- Higher mobility over wide range of densities
  For example, at $n \sim 1\times10^{11}$ $/cm^2$
  - Old : $\mu \sim 1.8\times10^{7}$ cm^2/Vs
  - New : $\mu \sim 3.6\times10^{7}$ cm^2/Vs

- We estimate a background impurity concentration of $\sim1\times10^{13}$ $/cm^3$
  - Equivalent to ~1 impurity per every 10 billion Ga/As atoms!

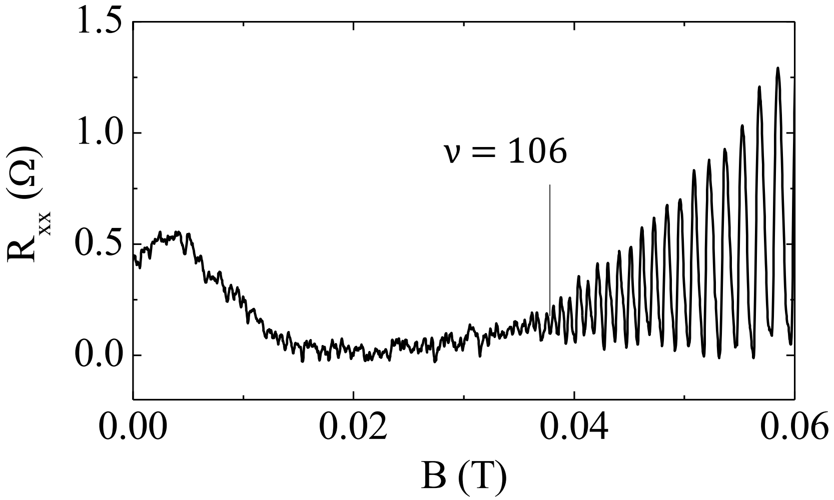


Magnetotransport of record-quality GaAs 2DESs



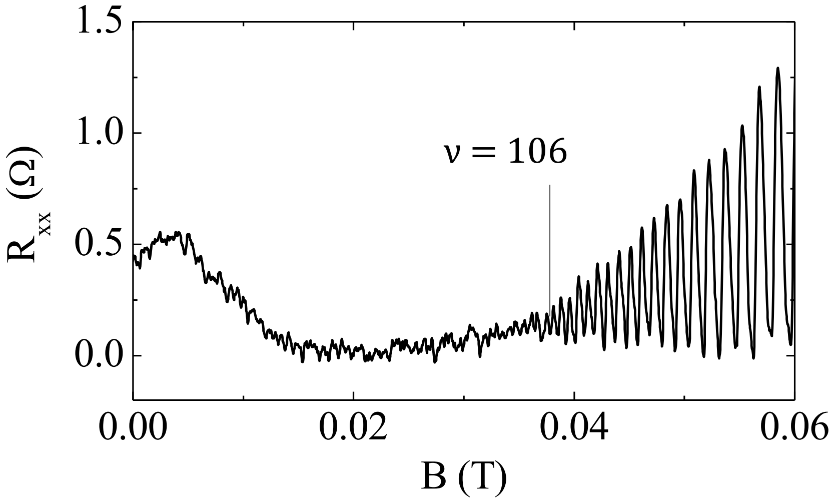
Extraordinary magnetoresistance observed in the new samples at low T!

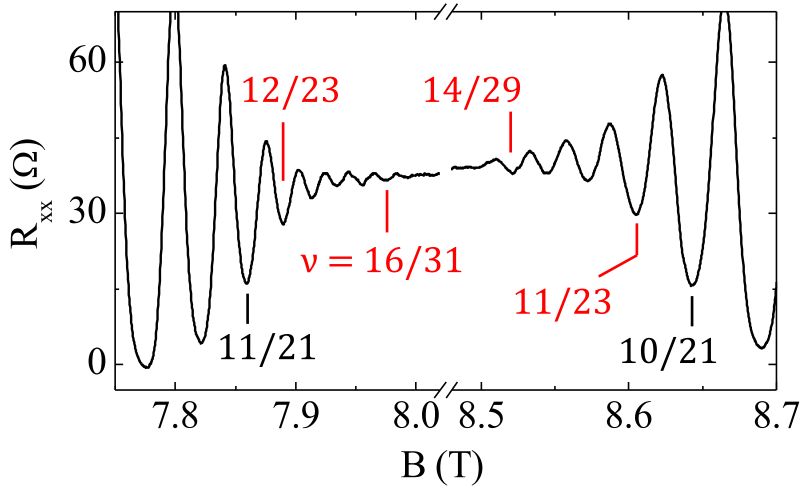
Magnetotransport of record-quality GaAs 2DESs



- SdH clearly resolvable up to ν = 106

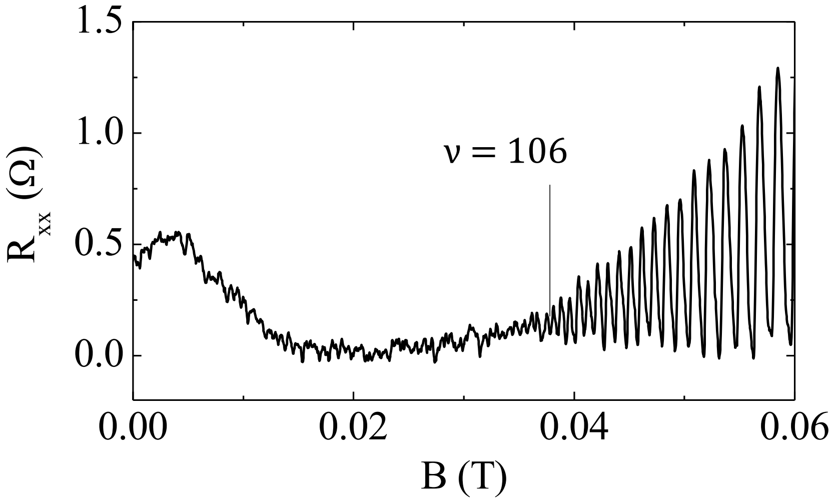
Magnetotransport of record-quality GaAs 2DESs

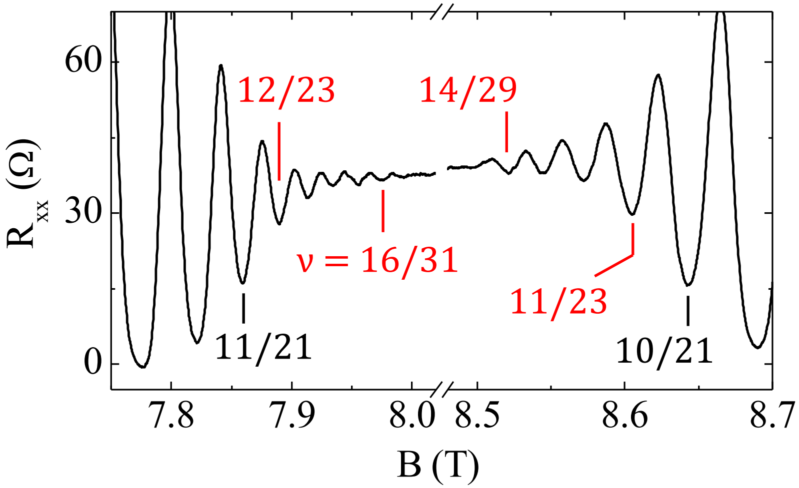


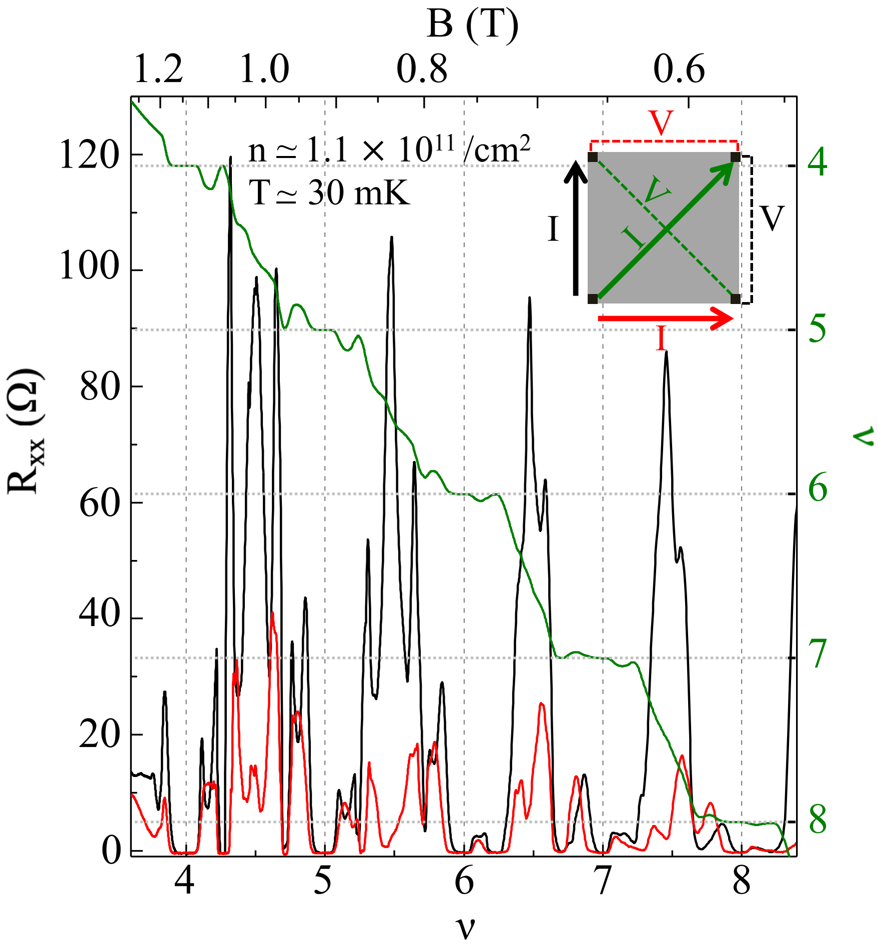


- SdH clearly resolvable up to ν = 106
- New FQHSs near ν = 1/2

Magnetotransport of record-quality GaAs 2DESs



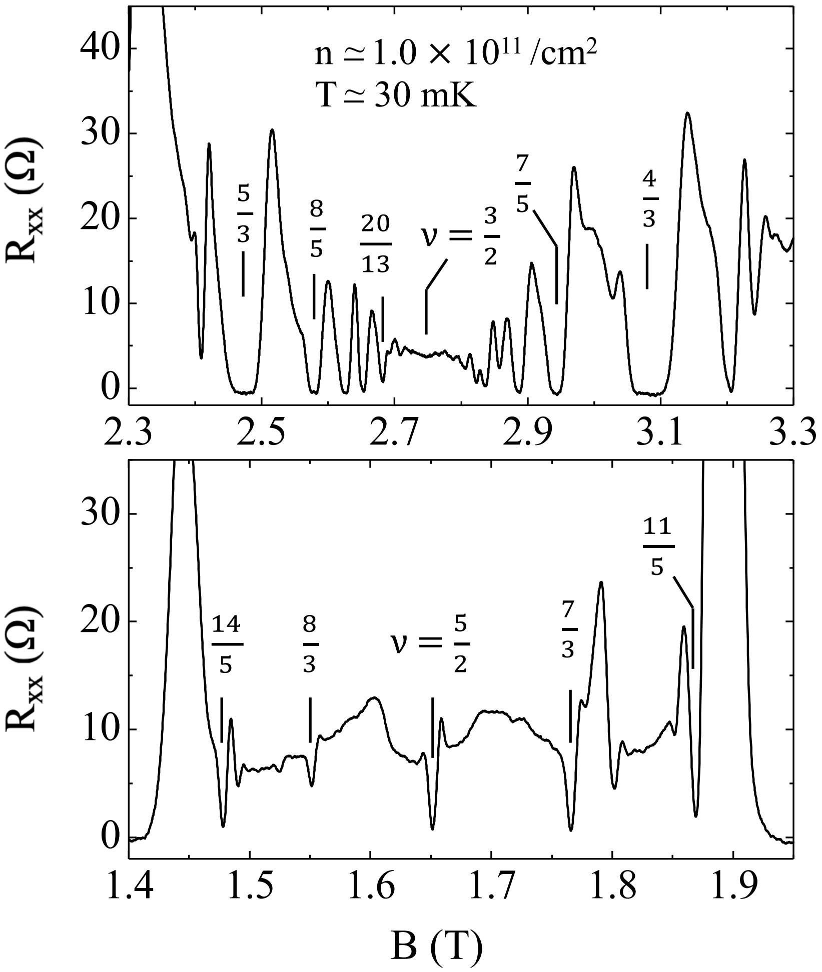




- SdH clearly resolvable up to ν = 106
- New FQHSs near ν = 1/2

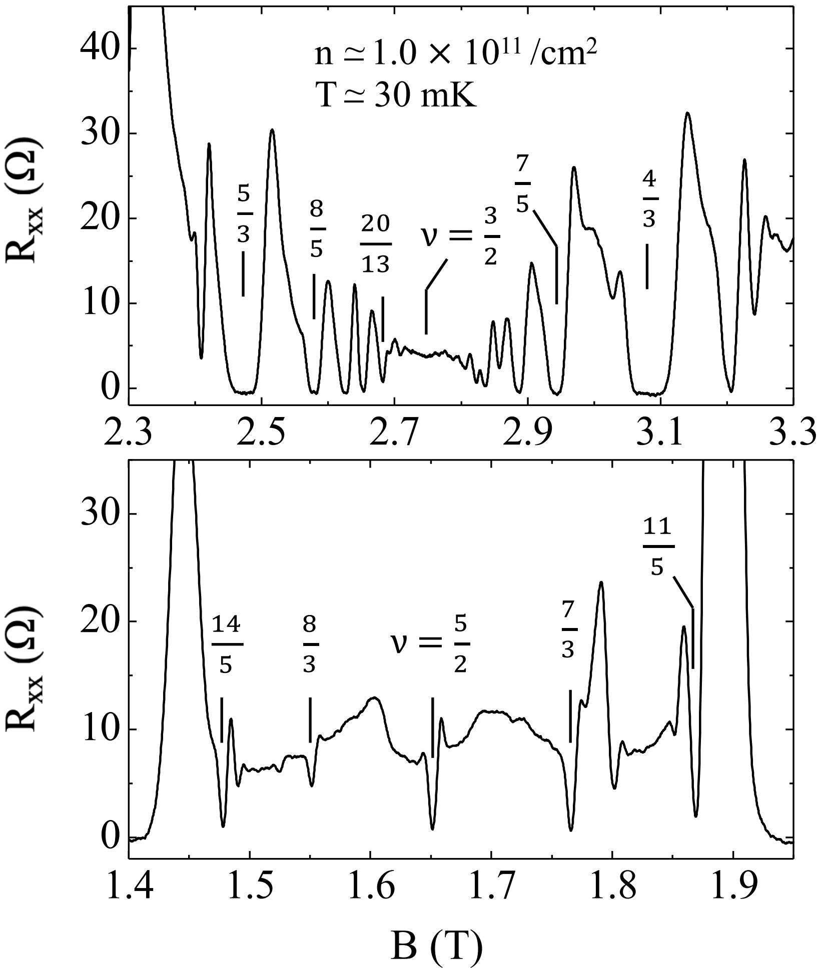
- Strong stripe/bubble phases

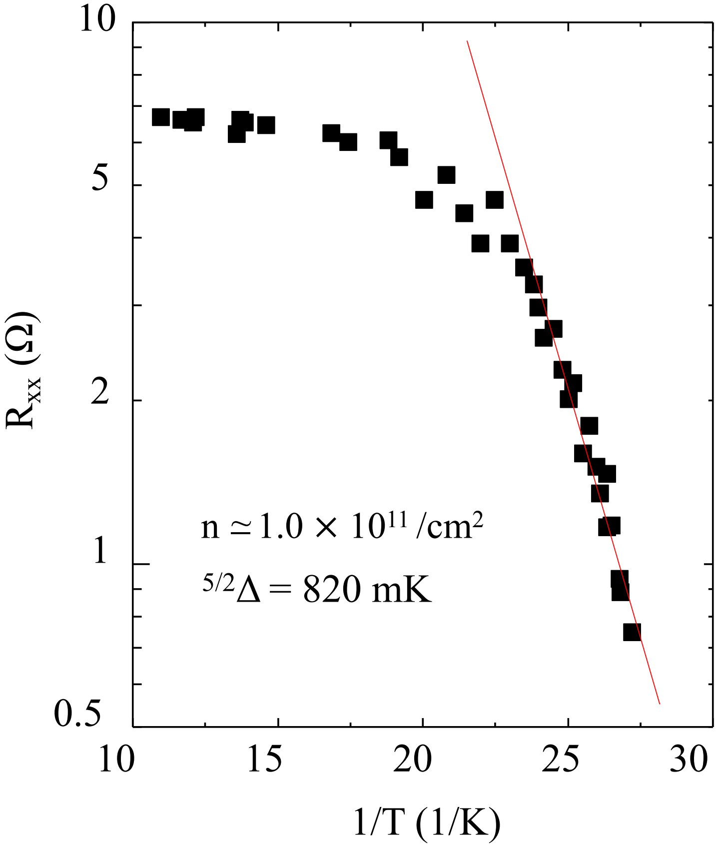
Magnetotransport of record-quality GaAs 2DESs



- Several fractional quantum Hall states near ν = 5/2, 3/2

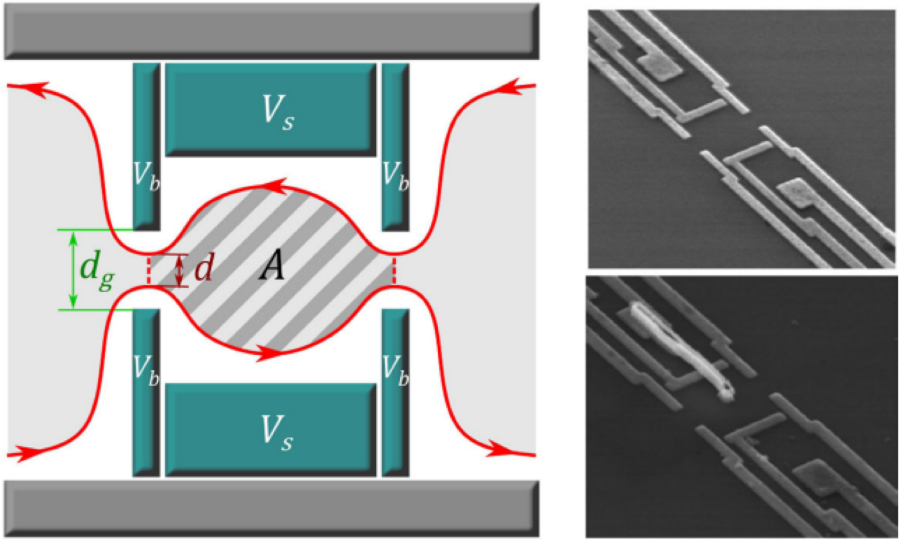
Magnetotransport of record-quality GaAs 2DESs



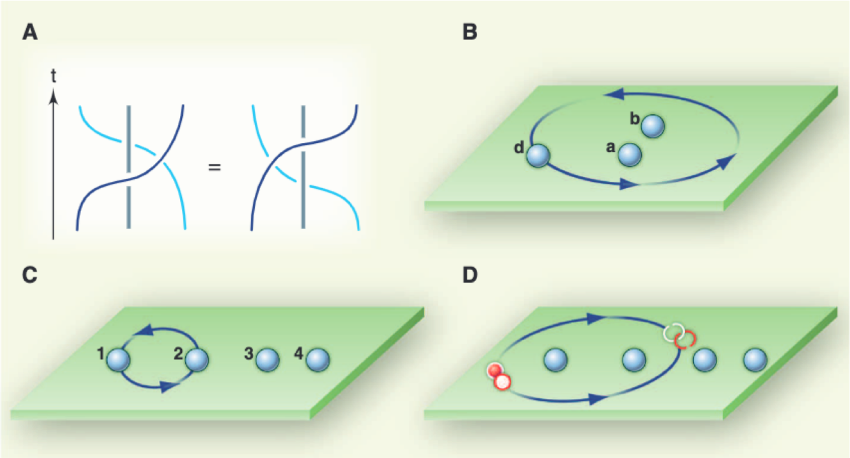


- Several fractional quantum Hall states near ν = 5/2, 3/2
- Record activation gap value of ~820 mK for ν = 5/2

New opportunities in quantum devices



R. L. Willett, Phys. Rev. X **13**, 011028 (2023)

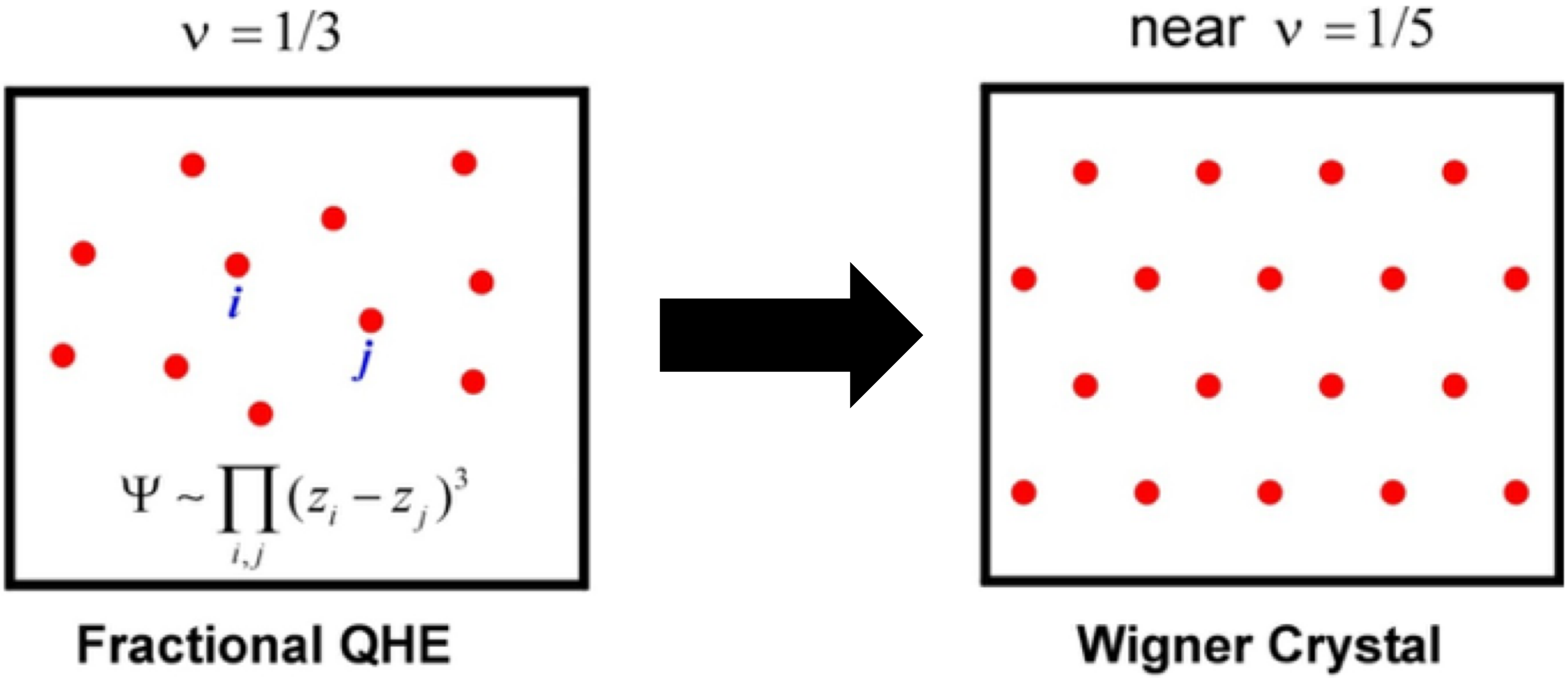


A. Stern, Science **339**, 1179 (2013)

- Braiding of non-Abelian particles for the operation of topological qubit with extremely long coherence times
- Difficult to realize previously due to high sample quality requirements

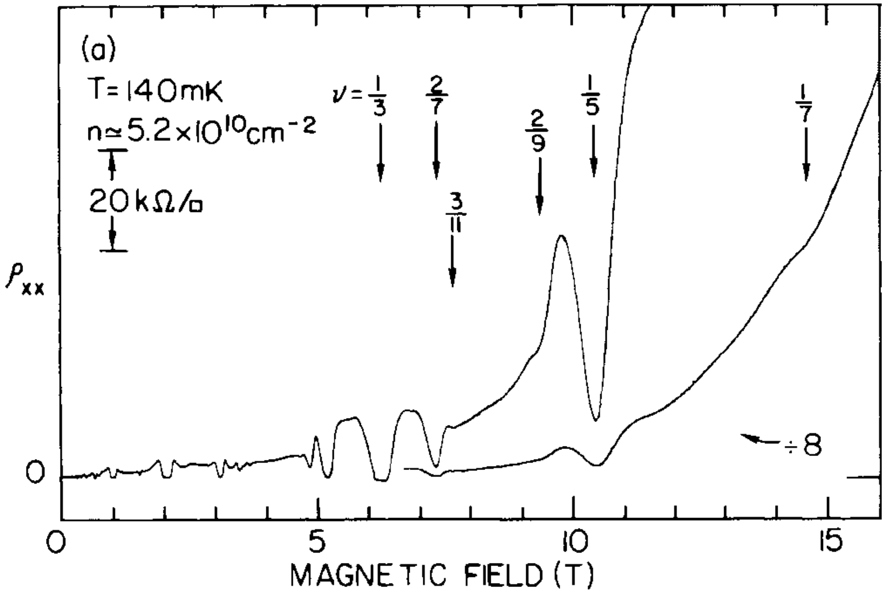
➡ Potential to utilize as Quantum memory

Controversy in the lowest Landau level



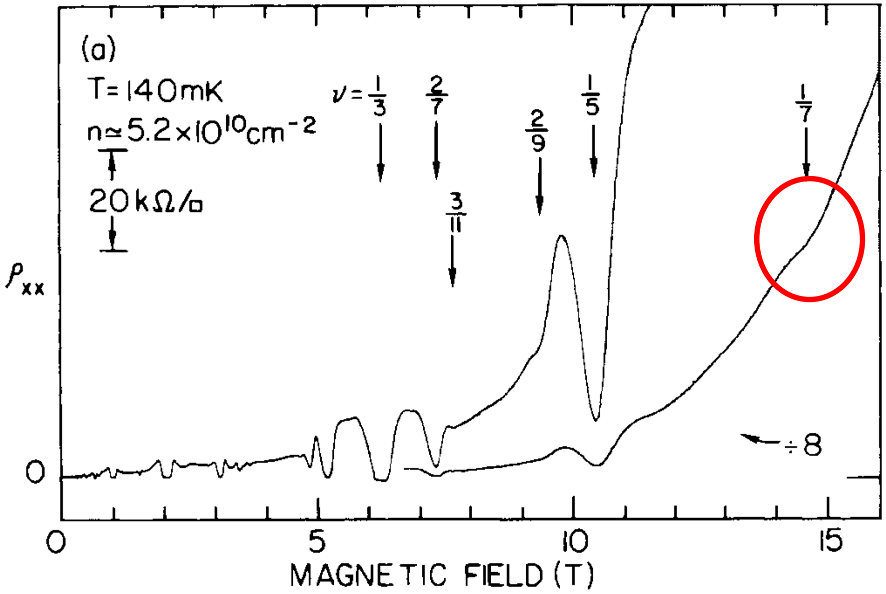
Theory suggests a ground state
transition somewhere $\nu \sim 1/6.5$

Controversy in the lowest Landau level



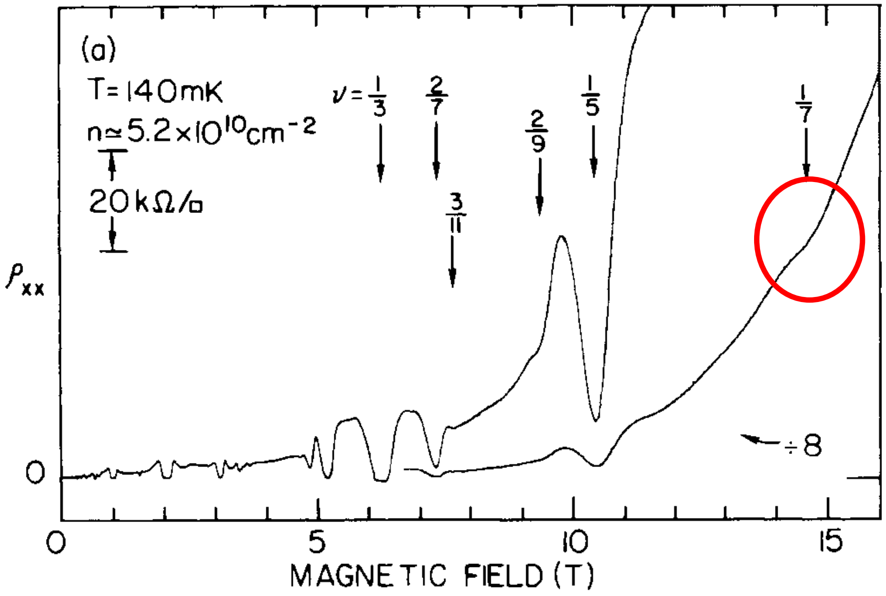
V. J. Goldman et al., Phys. Rev. Lett. 61, 881 (1988)

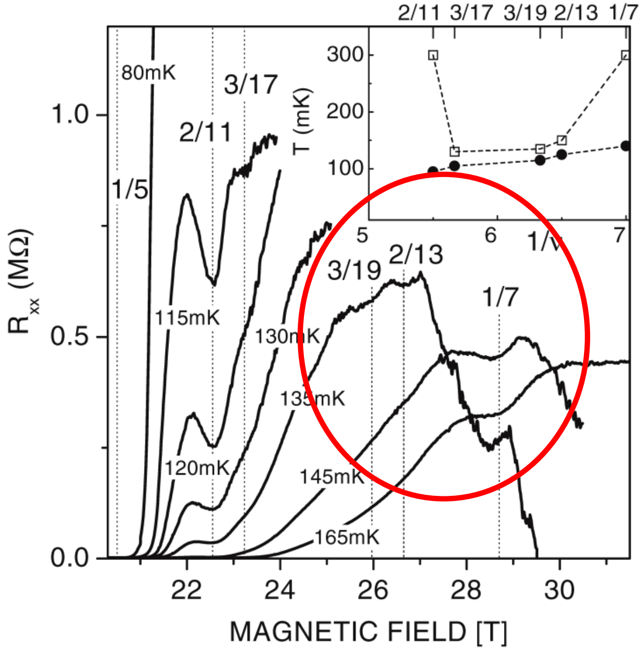
Controversy in the lowest Landau level

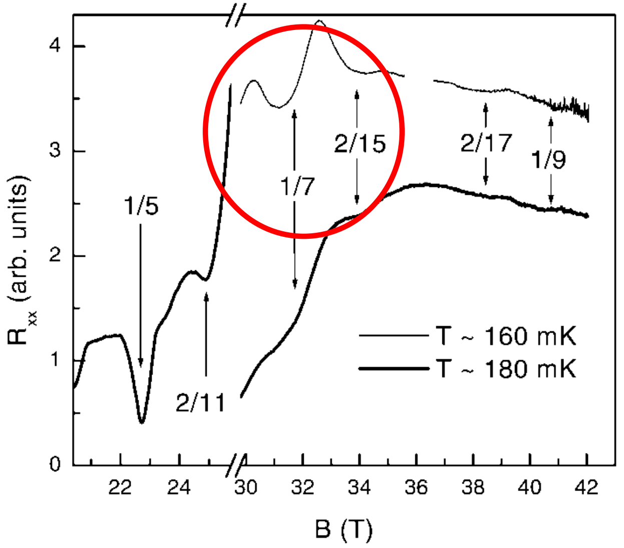


V. J. Goldman et al., Phys. Rev. Lett. 61, 881 (1988)

Controversy in the lowest Landau level



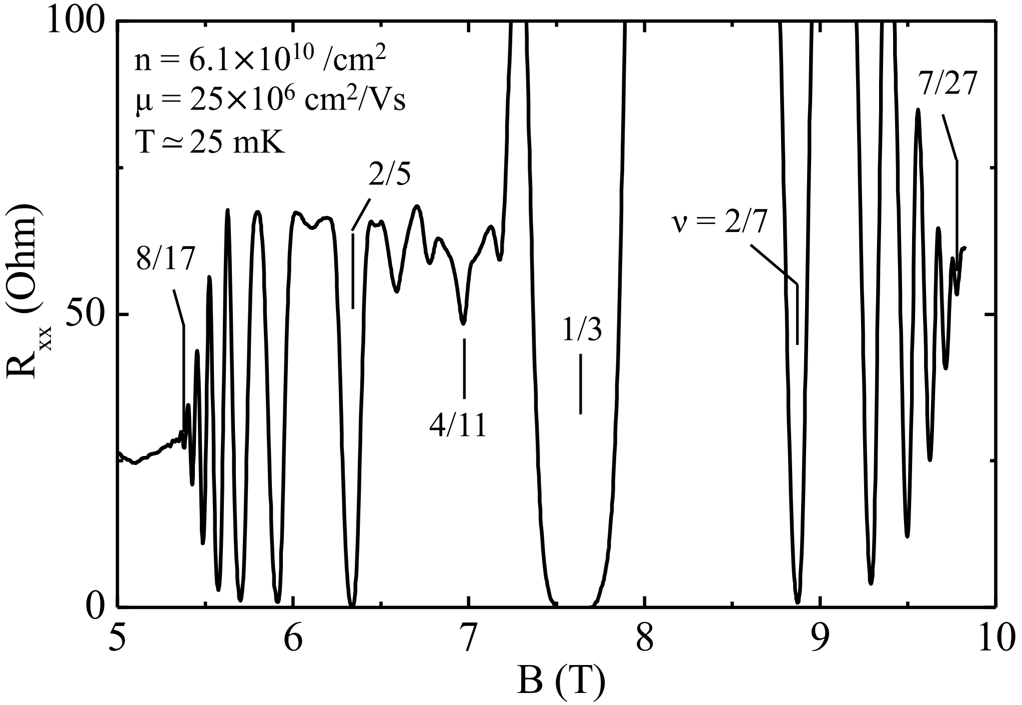


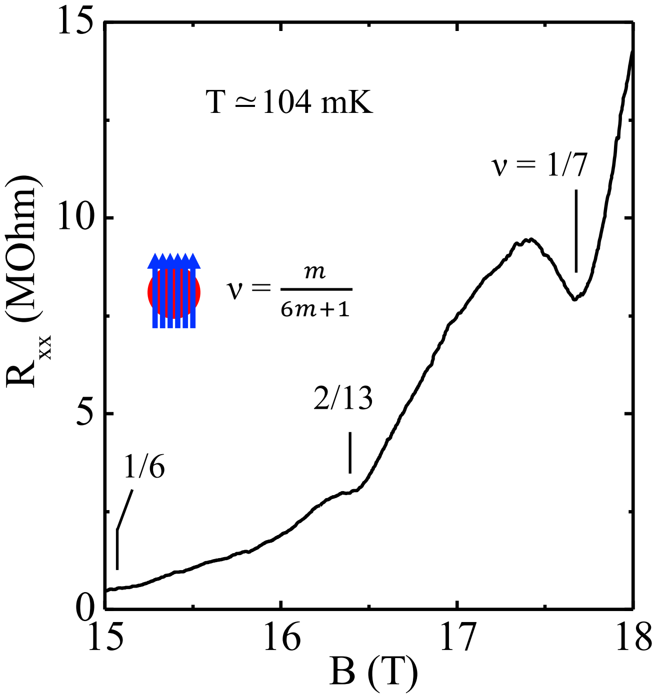


V. J. Goldman et al., Phys. Rev. Lett. 61, 881 (1988)

W. Pan et al., Phys. Rev. Lett. 88, 176802 (2002)

Record-quality GaAs 2DES : R_{xx} at $\nu = 1/7$

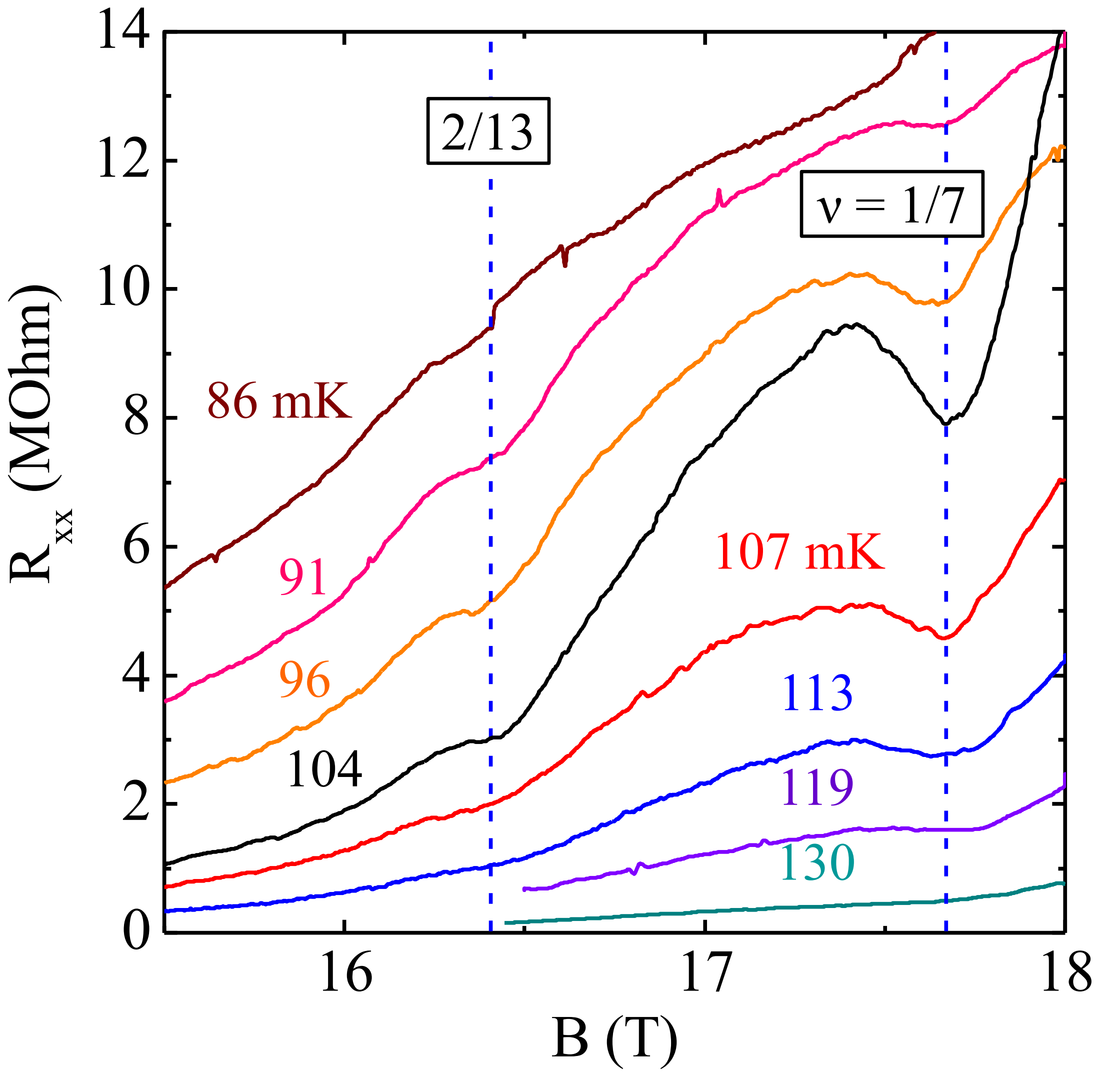




- Several high-order FQHSs observed near $\nu = 1/2$ and $1/4$ despite the low density
- Deep minimum observed in R_{xx} trace at $\nu = 1/7$, strongly suggestive of a six-flux composite-fermion-based FQHS

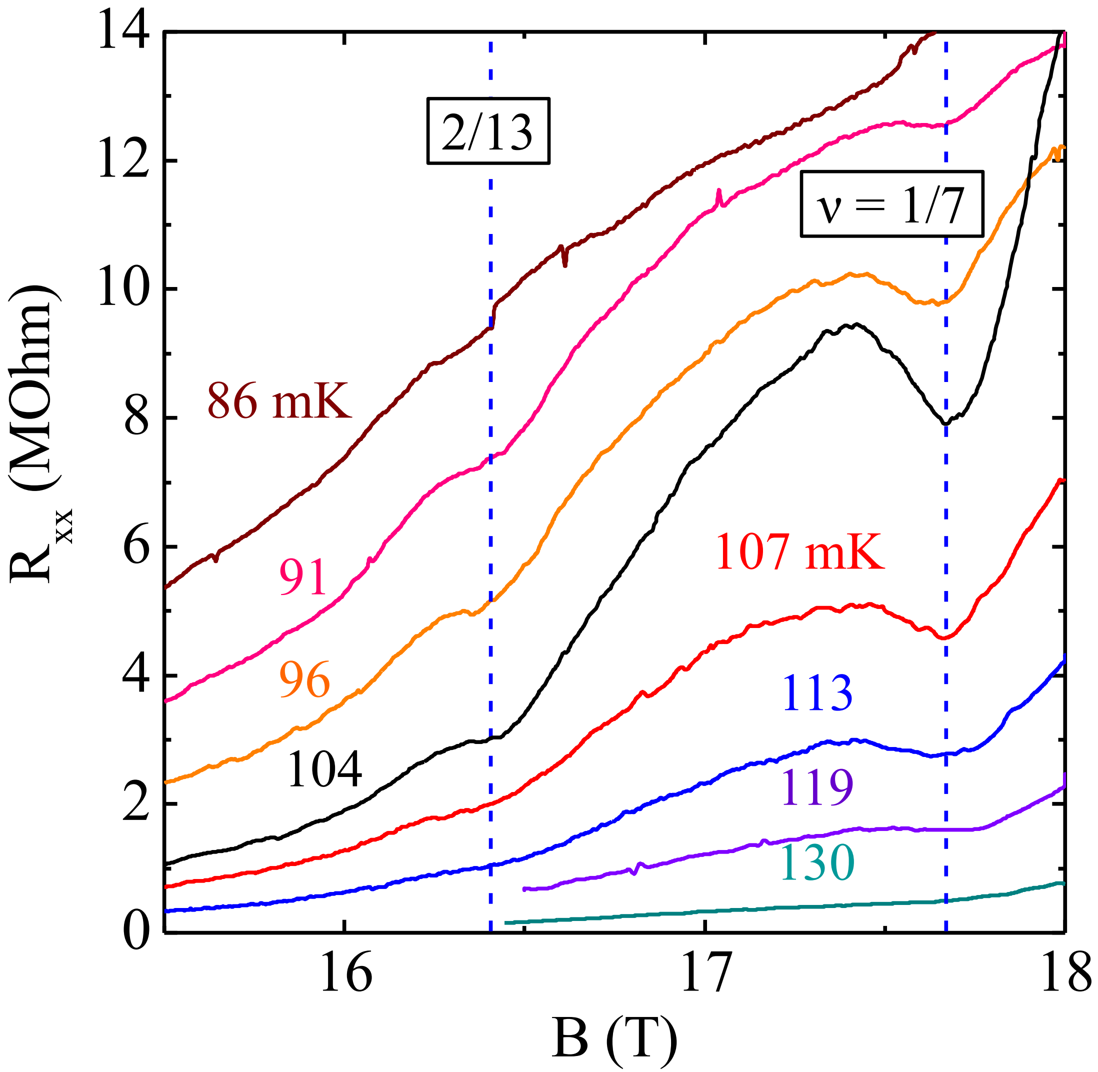
Y. J. Chung, Phys. Rev. Lett. **128**, 026802 (2022)

Temperature dependence of feature at ν =1/7



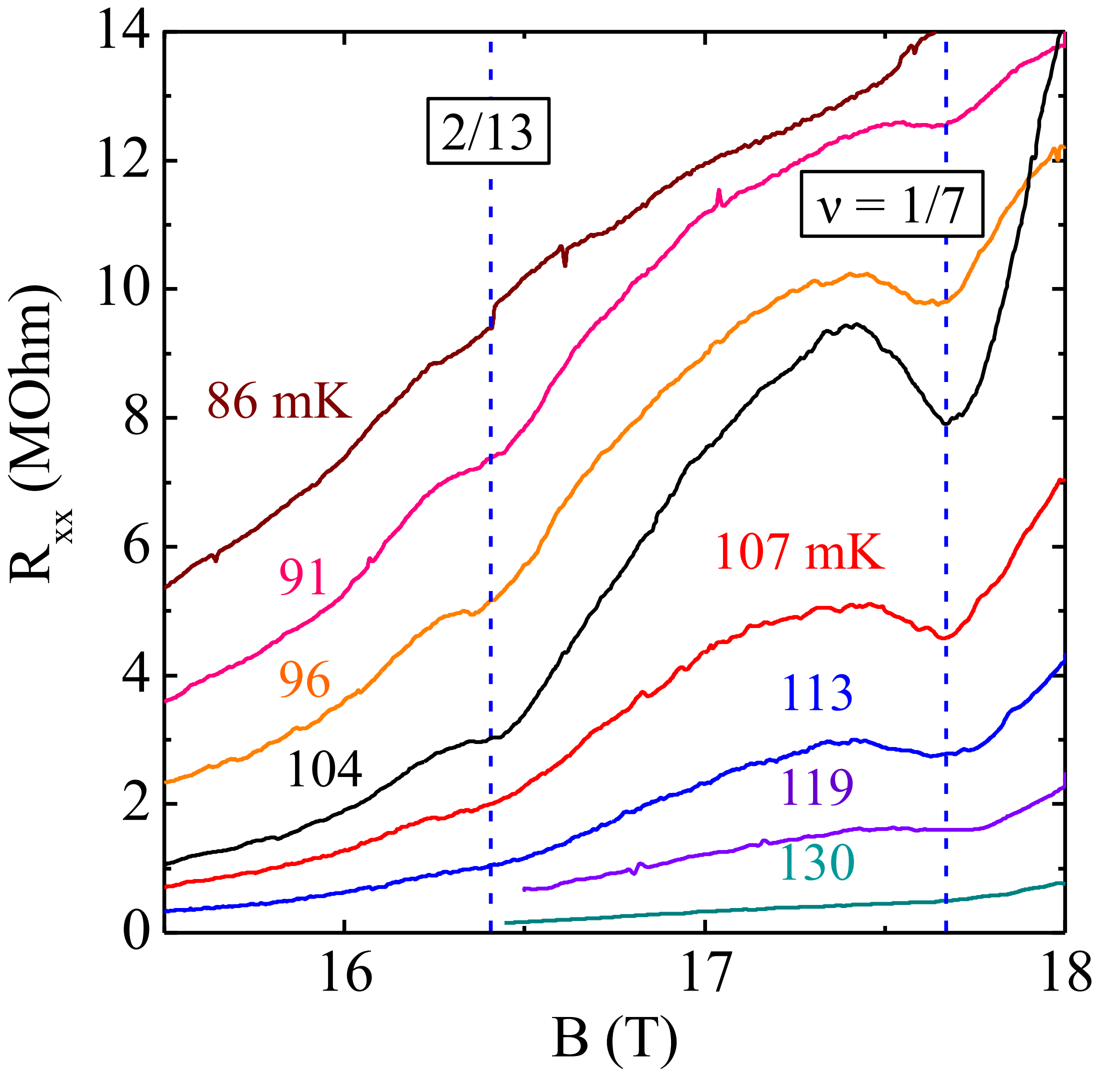
- Minimum is deepest at the intermediate temperature T = 104 mK

Temperature dependence of feature at ν =1/7



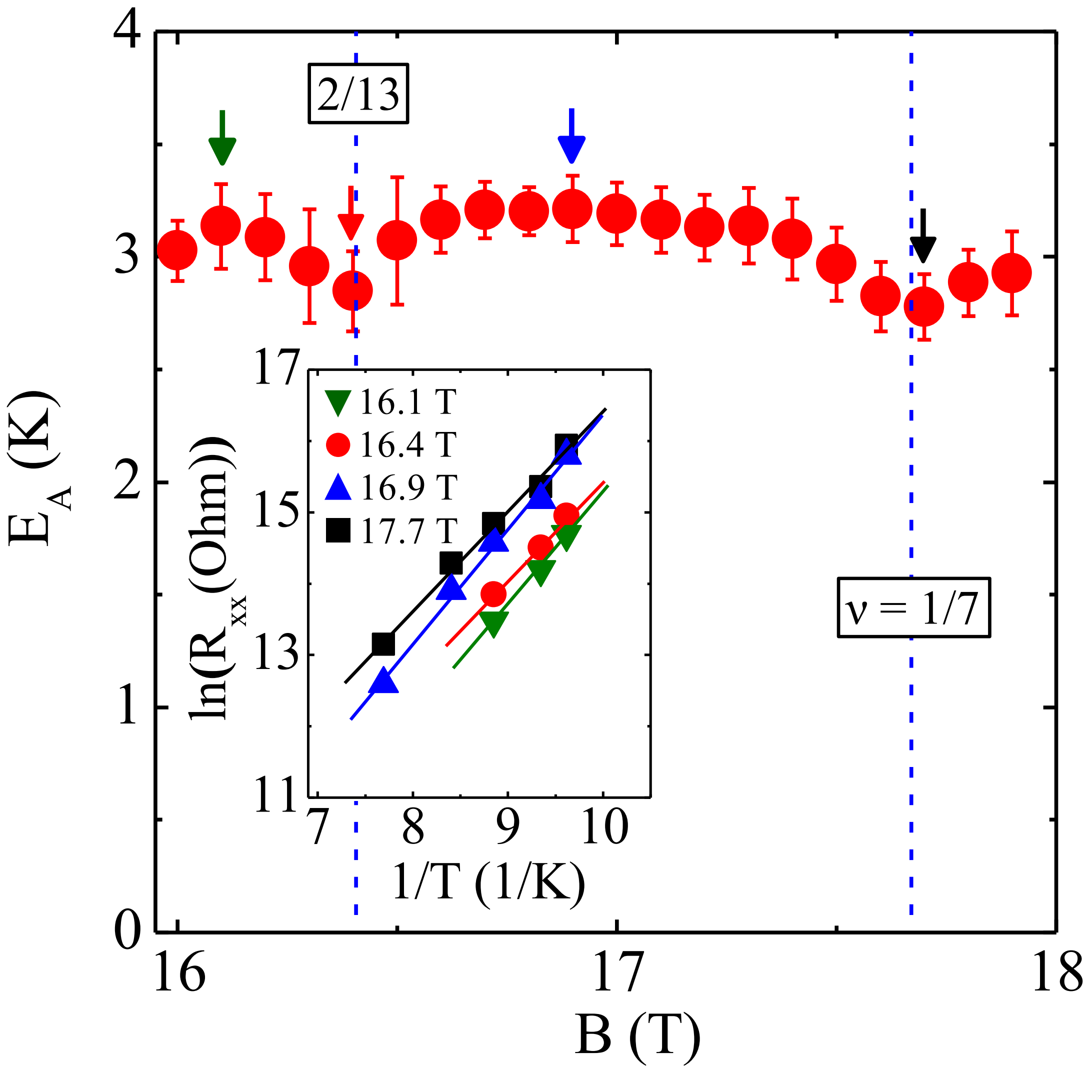
- Minimum is deepest at the intermediate temperature T = 104 mK
- Background insulating phases, most likely deriving from Wigner solids, dominate at lower temperatures
- Both the insulating phase and minimum weaken at higher temperatures

Temperature dependence of feature at ν =1/7



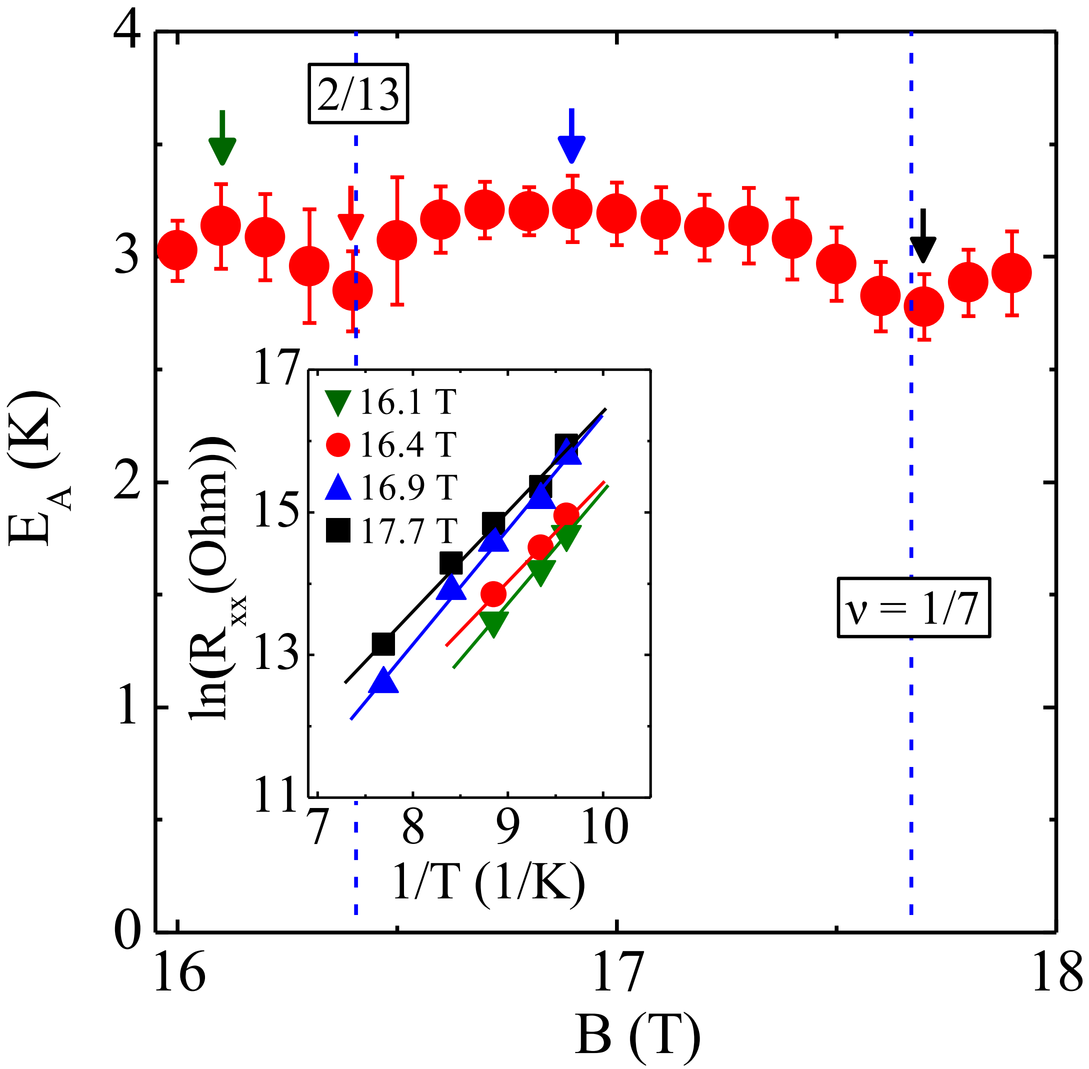
- Minimum is deepest at the intermediate temperature T = 104 mK
- Background insulating phases, most likely deriving from Wigner solids, dominate at lower temperatures
- Both the insulating phase and minimum weaken at higher temperatures
- Similar trend observed for feature at ν = 2/13

Activation energy analysis



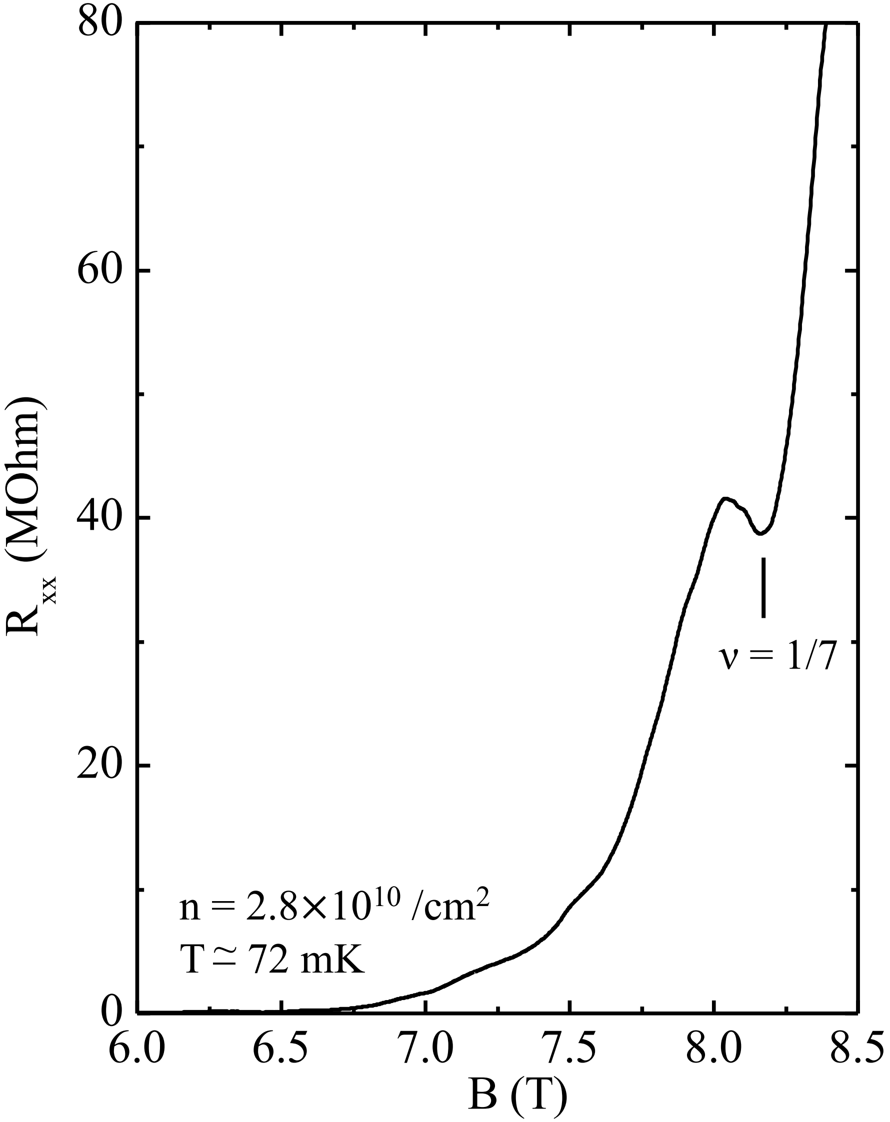
- Activation energy deduced from $R_{xx} \sim \exp(E_A/2kT)$ also display minima at ν = 1/7 and 2/13

Activation energy analysis



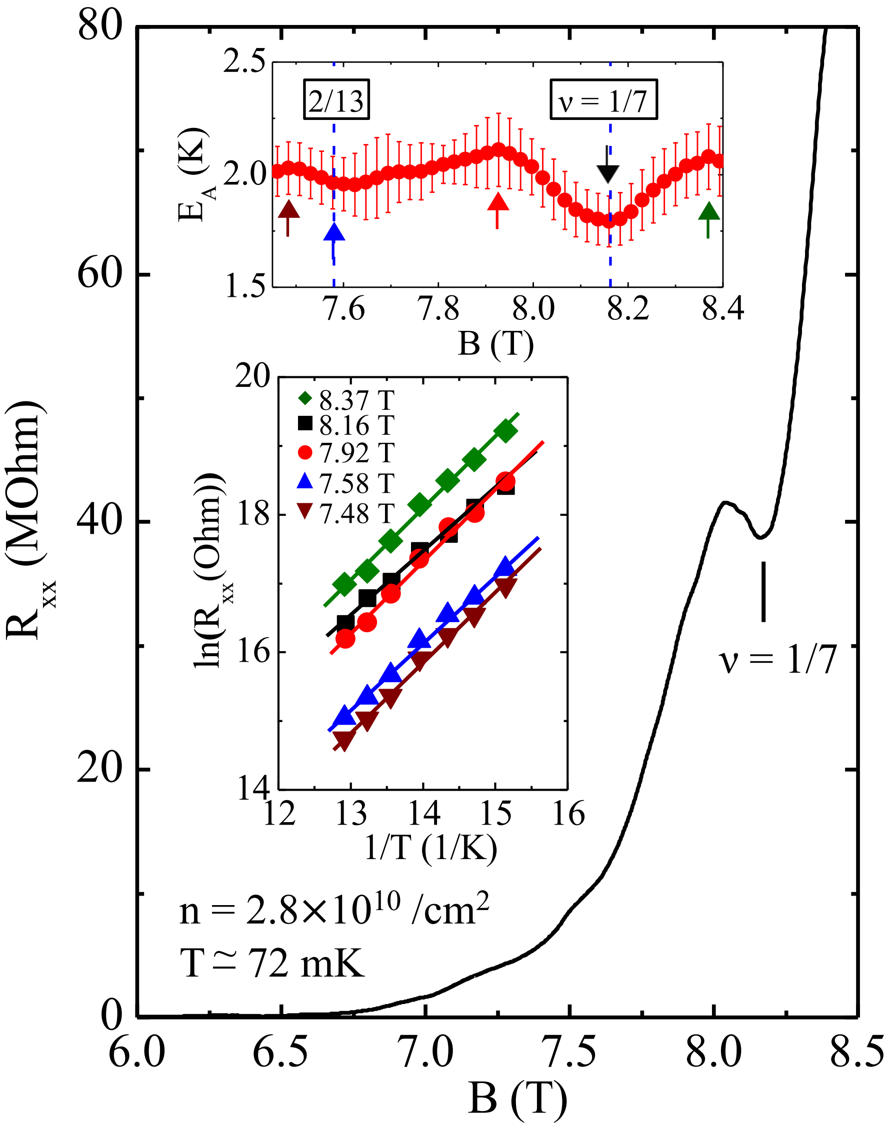
- Activation energy deduced from $R_{xx} \sim \exp(E_A/2kT)$ also display minima at ν = 1/7 and 2/13
- The E_A values are typically a factor of 2~3 larger than in literature (e.g., see H. W. Jiang et al., PRB 44, 8107 (1991))
- In fact, the E_A values we obtain at fillings $\nu \neq p/(2mp \pm 1)$ approach those calculated in theory (see A. C. Archer and J. K. Jain, PRB 90, 201309(R) (2014))

Features near ν =1/7 in other samples



- Features in R_{xx} trace near ν = 1/7 are very similar even in much lower density sample

Features near ν =1/7 in other samples

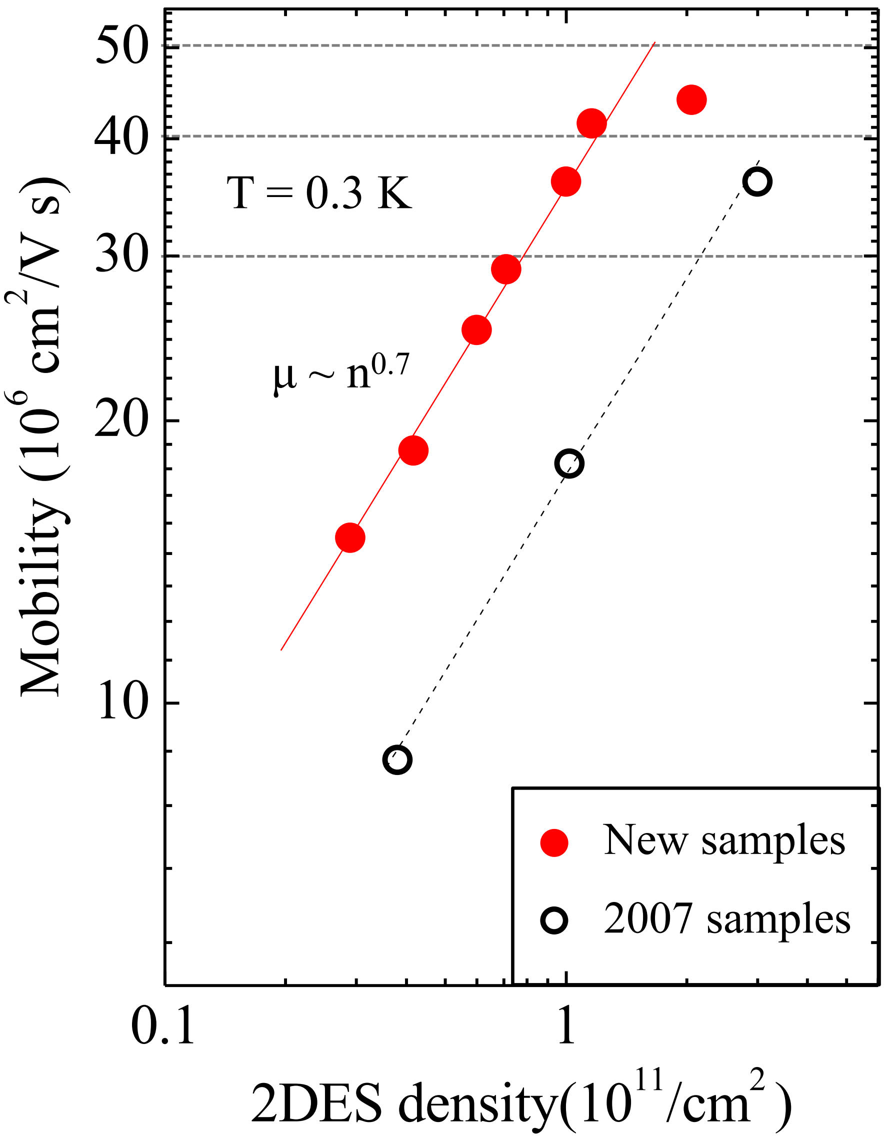


- Features in R_{xx} trace near ν = 1/7 are very similar even in much lower density sample

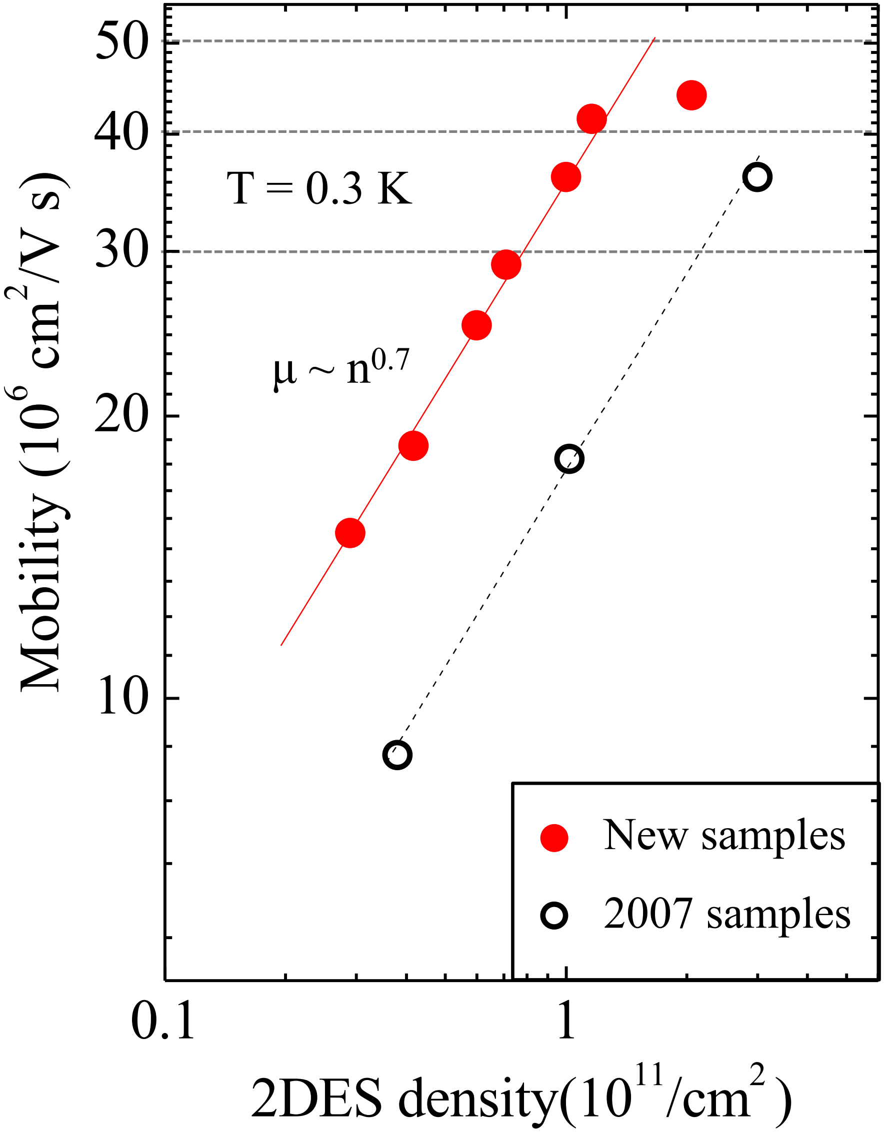
- Activation analysis also yields very similar results, showing minima at ν = 1/7 and 2/13

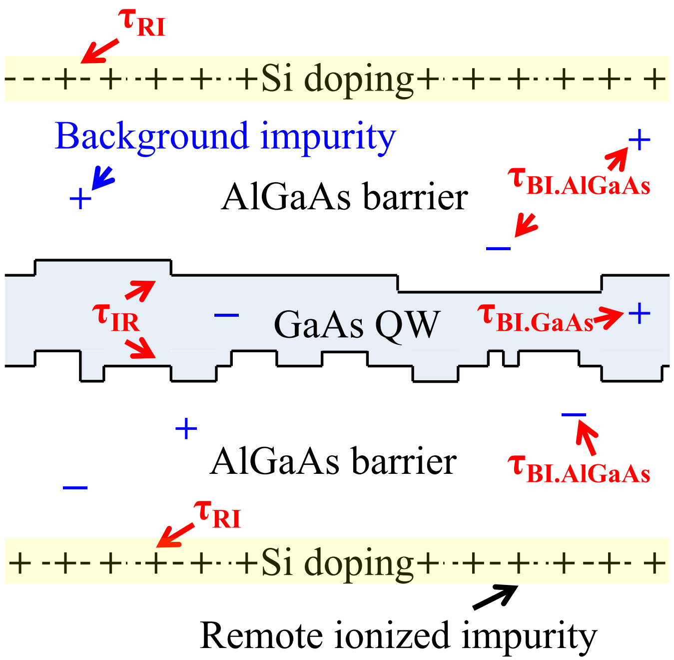
- The E_A values are smaller than for the high density sample, consistent with what is expected for 2DESs evaluated at lower magnetic fields

What's next? $\mu = 100\times10^6$ cm^2/Vs and beyond



What's next? $\mu = 100{\times}10^6\ \mathrm{cm^2/Vs}$ and beyond

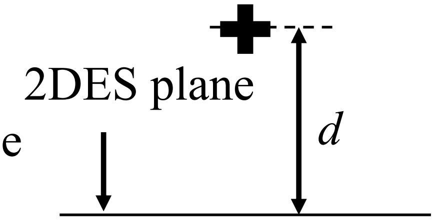




Y. J. Chung, Phys. Rev. B **106**, 075134 (2022)

Model set up – Charged impurity scattering

- For charge based scattering, we build up from an expression for scattering from 2D sheet of impurities a distance *d* away from the 2DES



- Assume elastic scattering and start from Fermi's golden rule

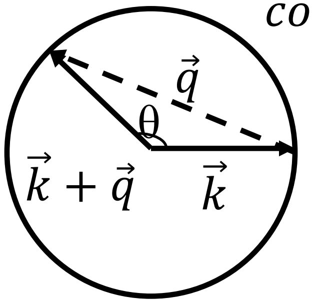
$$\frac{1}{\tau} = \frac{2\pi}{\hbar} \int \left|\widetilde{V}\,(\vec{q})\right|^2 \delta\left[\varepsilon\left(\vec{k}+\vec{q}\right) - \varepsilon\left(\vec{k}\right)\right] \frac{d^2\vec{q}}{(2\pi)^2}$$

- Weigh scattering by (1-cosθ)=$q^2/2k^2$ for efficacy in deterring transport

$$\frac{1}{\tau_{tr}} = \frac{2\pi}{\hbar} \int \frac{q^2}{2k^2} \left|\widetilde{V}\,(\vec{q})\right|^2 \delta\left[\varepsilon\left(\vec{k}+\vec{q}\right) - \varepsilon\left(\vec{k}\right)\right] \frac{d^2\vec{q}}{(2\pi)^2}$$

use $\varepsilon(k) = \frac{\hbar^2 k^2}{2m^*}$

$$\frac{1}{\tau_{tr}} = \frac{m^*}{2\pi\hbar^3 k^3} \int_0^{2k} \left|\widetilde{V}\,(\vec{q})\right|^2 \frac{q^2 dq}{\sqrt{1-(\frac{q}{2k})^2}}$$



$$q = 2k\, sin\frac{\theta}{2}$$

$$cos\theta = cos^2\left(\frac{\theta}{2}\right) - sin^2\left(\frac{\theta}{2}\right)$$

$$1 - cos\theta = 2sin^2\left(\frac{\theta}{2}\right)$$

$$1 - cos\theta = \frac{q^2}{2k^2}$$

Model set up – Charged impurity scattering

- Use the Thomas-Fermi approximation assuming zero temperature

$$\widetilde{V}\,(q) = n_{imp}\frac{e^2}{2\varepsilon_0\varepsilon_b}\frac{e^{-qd}}{q+q_{TF}} \qquad \text{with} \qquad q_{TF} = \frac{m^*}{2\pi\varepsilon_0\varepsilon_b\hbar^2}$$

being the TF screening wavevector

for a sheet of charge placed a distance *d* from the 2D carrier plane

- Scattering rate for 2D plane of charged sheet impurities is then

$$\boxed{\frac{1}{\tau_{tr}} = n_{imp}\frac{m^*}{2\pi\hbar^3 k_F^3}\left(\frac{e^2}{2\varepsilon_0\varepsilon_b}\right)^2\int_0^{2k_F}\frac{e^{-2qd}}{(q+q_{TF})^2}\frac{q^2dq}{\sqrt{1-(\frac{q}{2k_F})^2}}}$$

Remote ionized impurity scattering

Specify n_{imp}, d

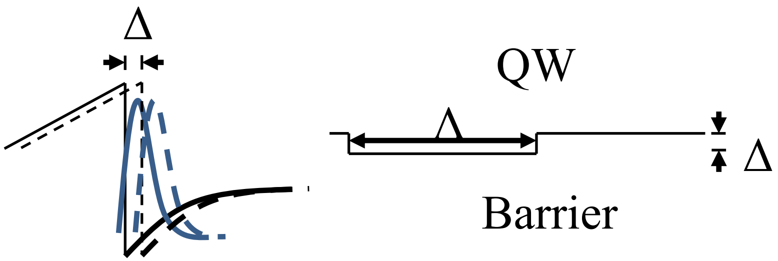
Background impurity scattering

Specify n_{imp}, integrate expression for $1/\tau$ over QW or barrier

- Use Drude model to deduce mobility $\mu = e\tau/m^*$

Model set up – Interface roughness scattering

- The scattering potential for interface roughness comes from the sudden change in the charge distribution



- For a symmetric quantum well

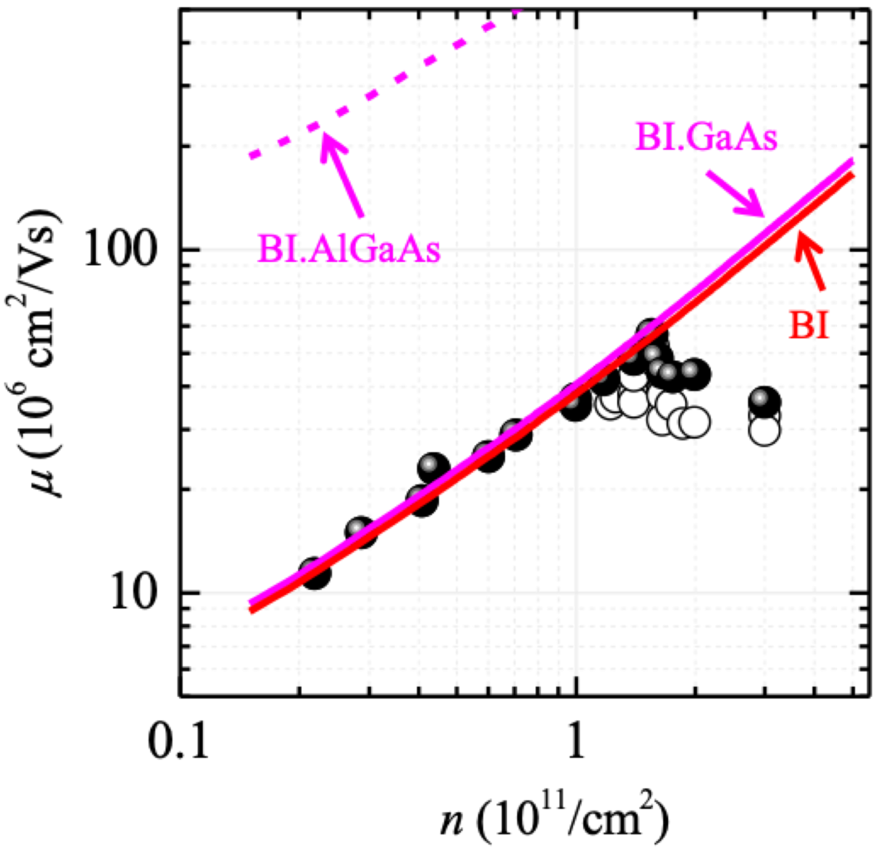
$$\frac{1}{\tau_{IR}} = \frac{4\pi m^* E_0^2 \Delta^2 \Lambda^2}{\hbar^3 (L + \sqrt{\frac{2\hbar^2}{m^*(V_0 - E_0)}})^2} f(\Lambda, k_F),$$

with E_0 being the ground-state energy of the QW and L the QW width

$$f(\Lambda, k_F) = \frac{1}{2\pi k_F^3} \int_0^{2k_F} (\frac{q}{q + q_{TF}})^2 \frac{e^{(-\frac{\Lambda^2 q^2}{4})} q^2 \, dq}{\sqrt{1 - (q/2k_F)^2}},$$

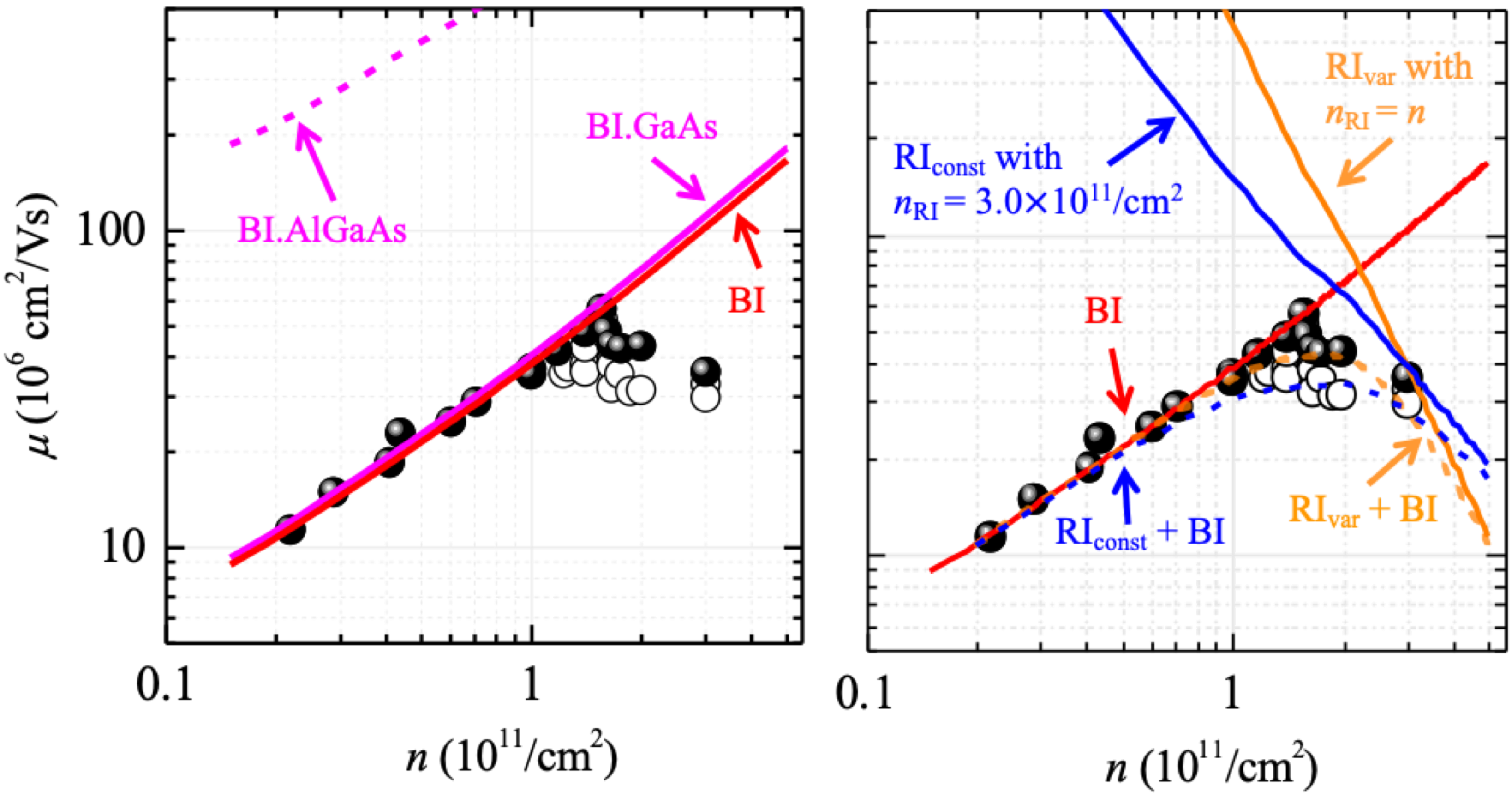
- Use Drude model to deduce mobility $\mu = e\tau/m^*$

Comparison with data – Charged based scattering



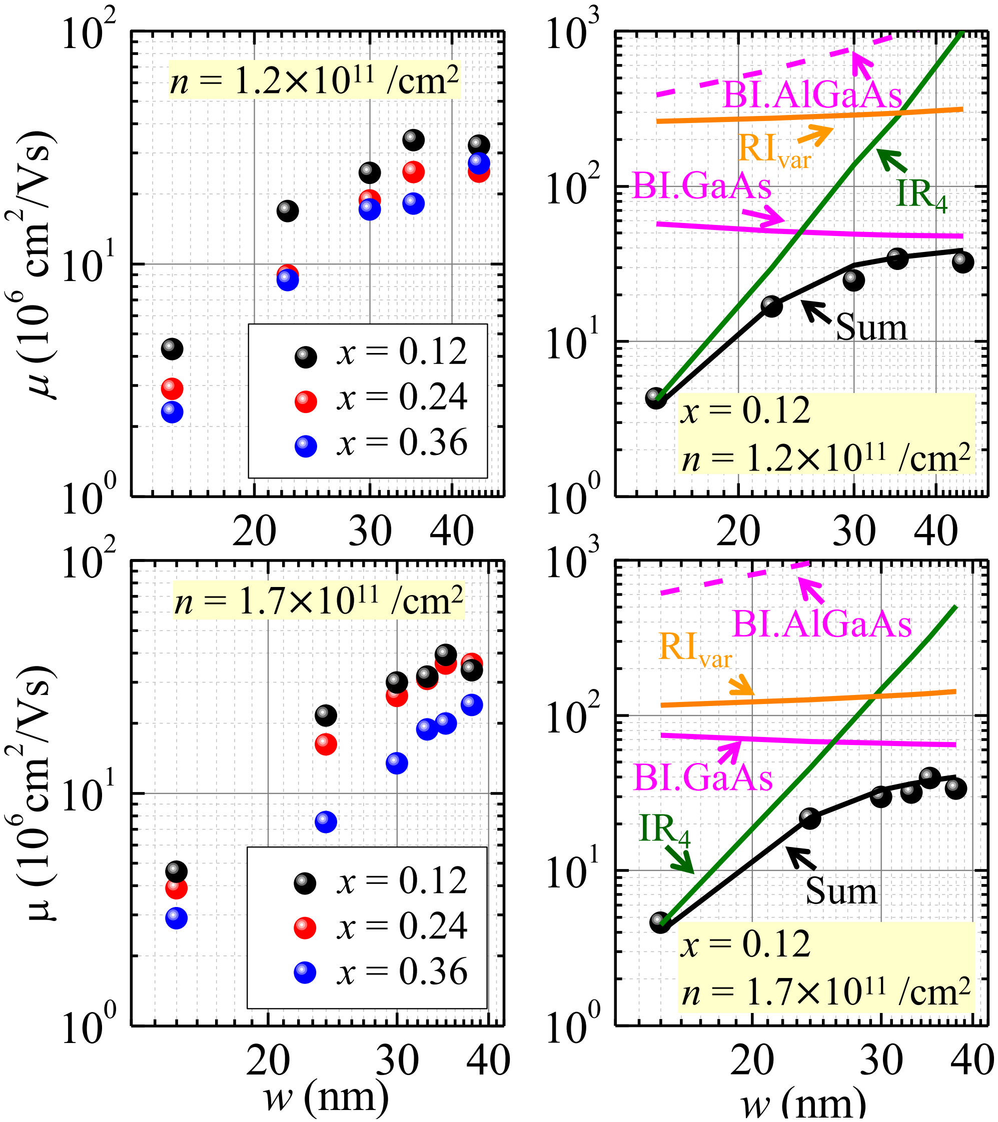
- Background impurity scattering fits well for low 2DES density data points
- Other models are necessary to figure out what is going on at higher densities

Comparison with data – Charged based scattering



- Remote ionized impurity scattering potentially explains the fall in mobility at higher densities

Comparison with data – Interface roughness

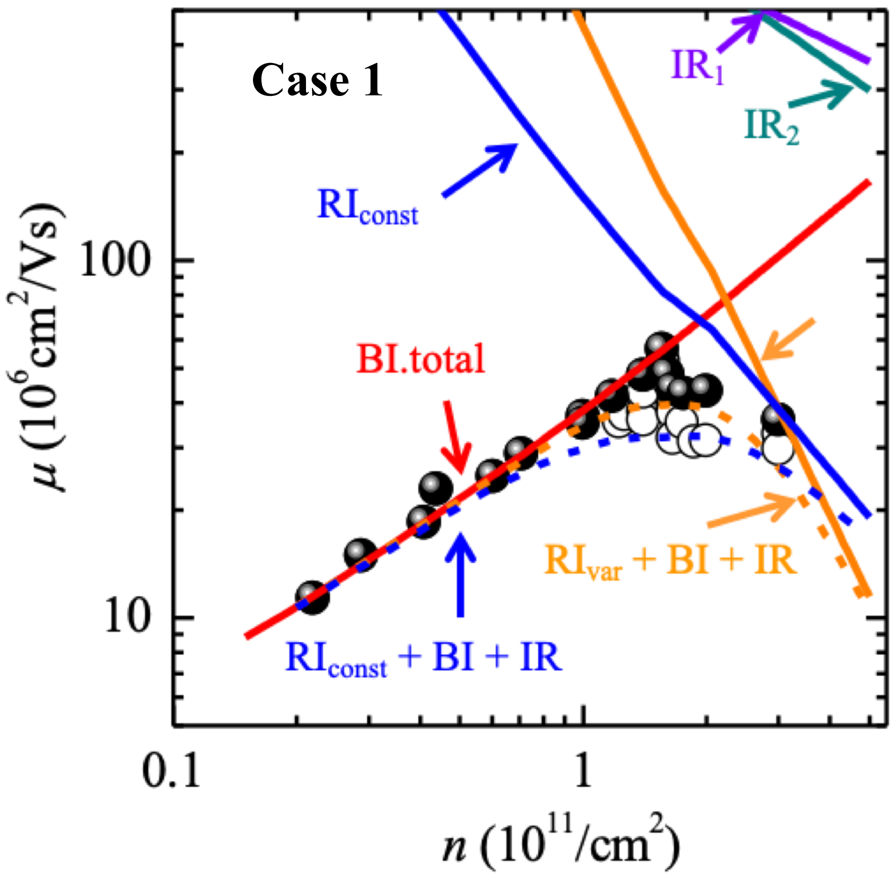


- Separate set of samples with QW width as main variable to deduce reasonable values for Λ, Δ

- Fit for different barrier heights corresponding to x=0.12, 0.24, 0.36

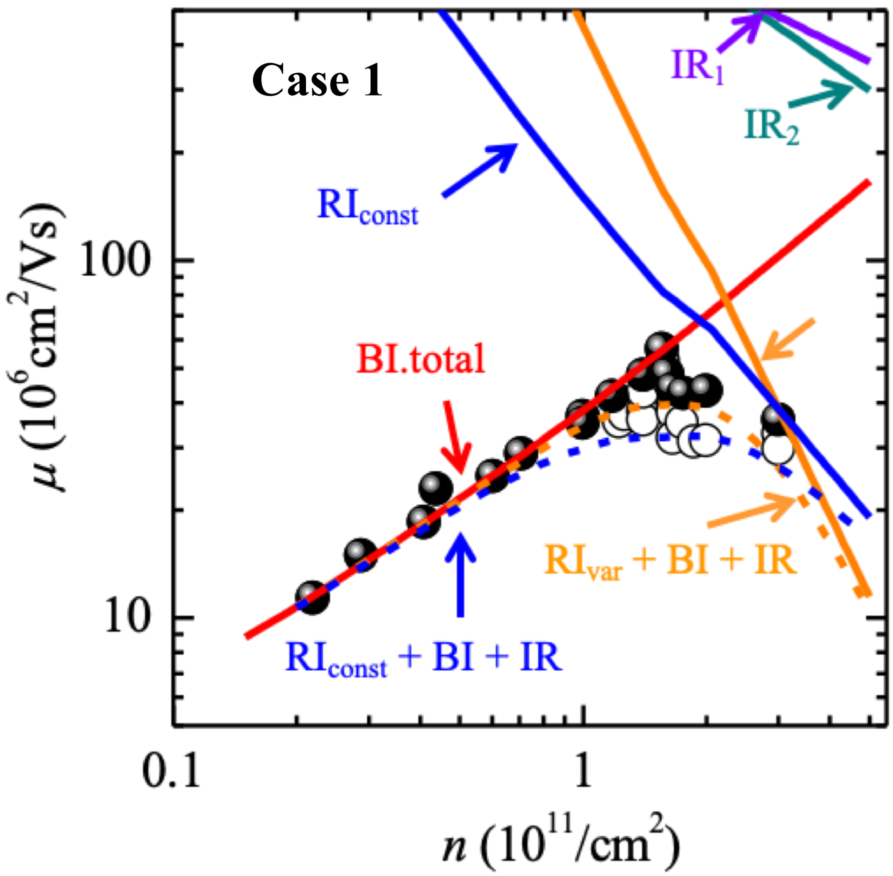
- End up with 4 different sets of Λ, Δ that can explain the data

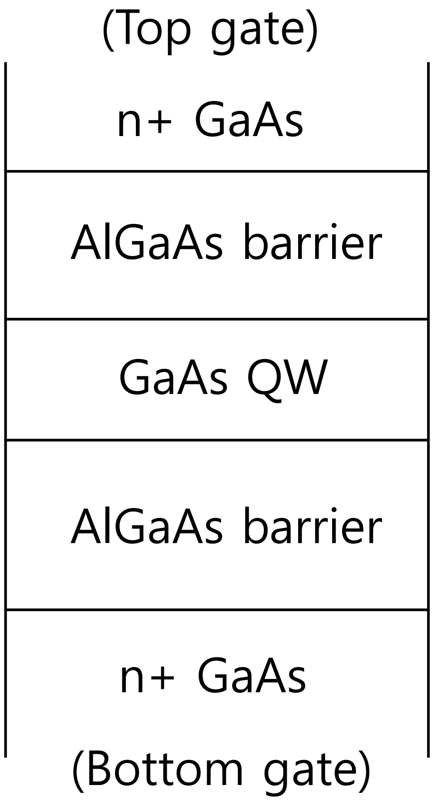
Comparison with data – Holistic picture



- Scattering at high electron densities almost fully determined by RI scattering

Comparison with data – Holistic picture




(Top gate)

n+ GaAs

AlGaAs barrier

GaAs QW

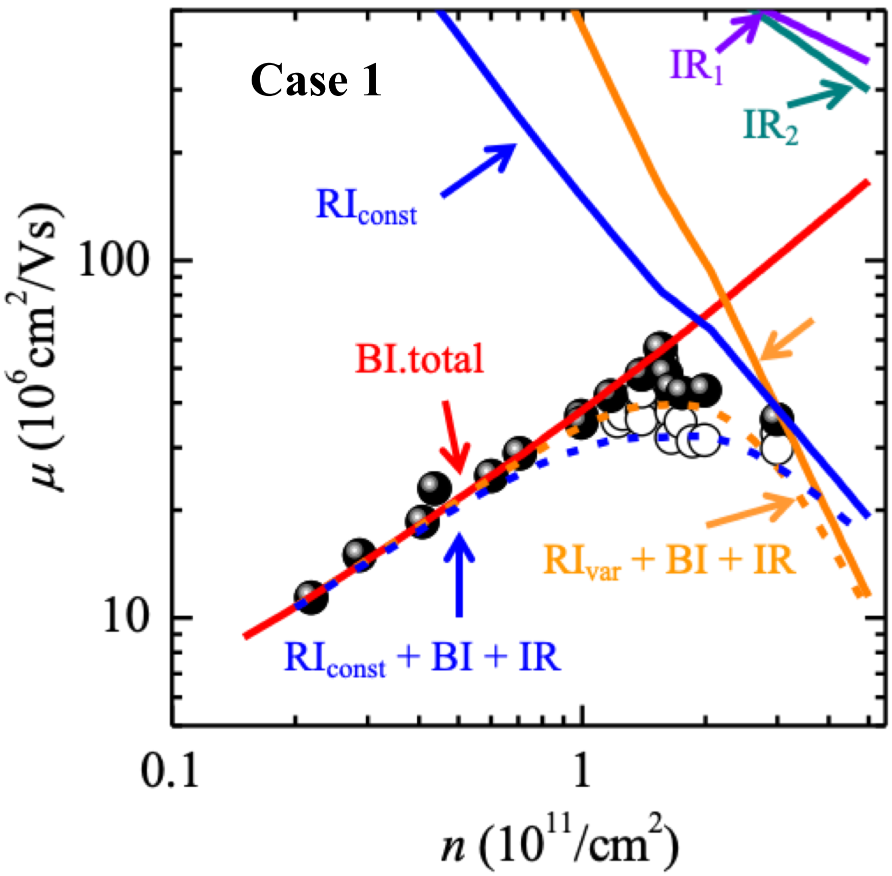
AlGaAs barrier

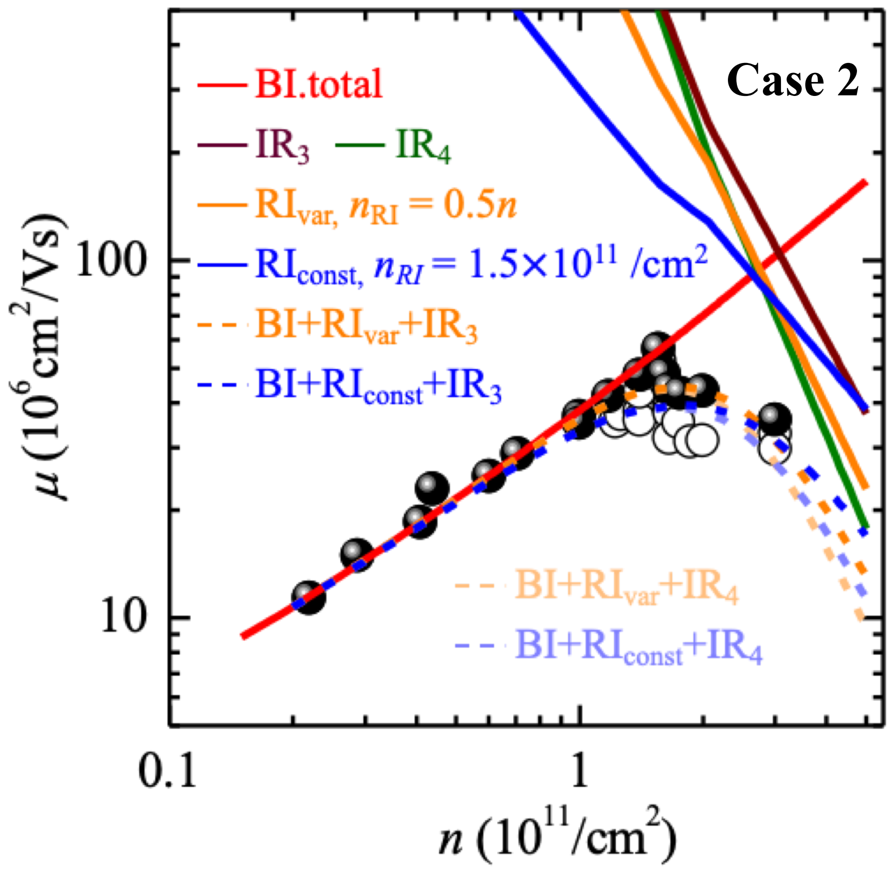
n+ GaAs

(Bottom gate)

- Scattering at high electron densities almost fully determined by RI scattering
- Implement structure with symmetric gating from both sides

Comparison with data – Holistic picture



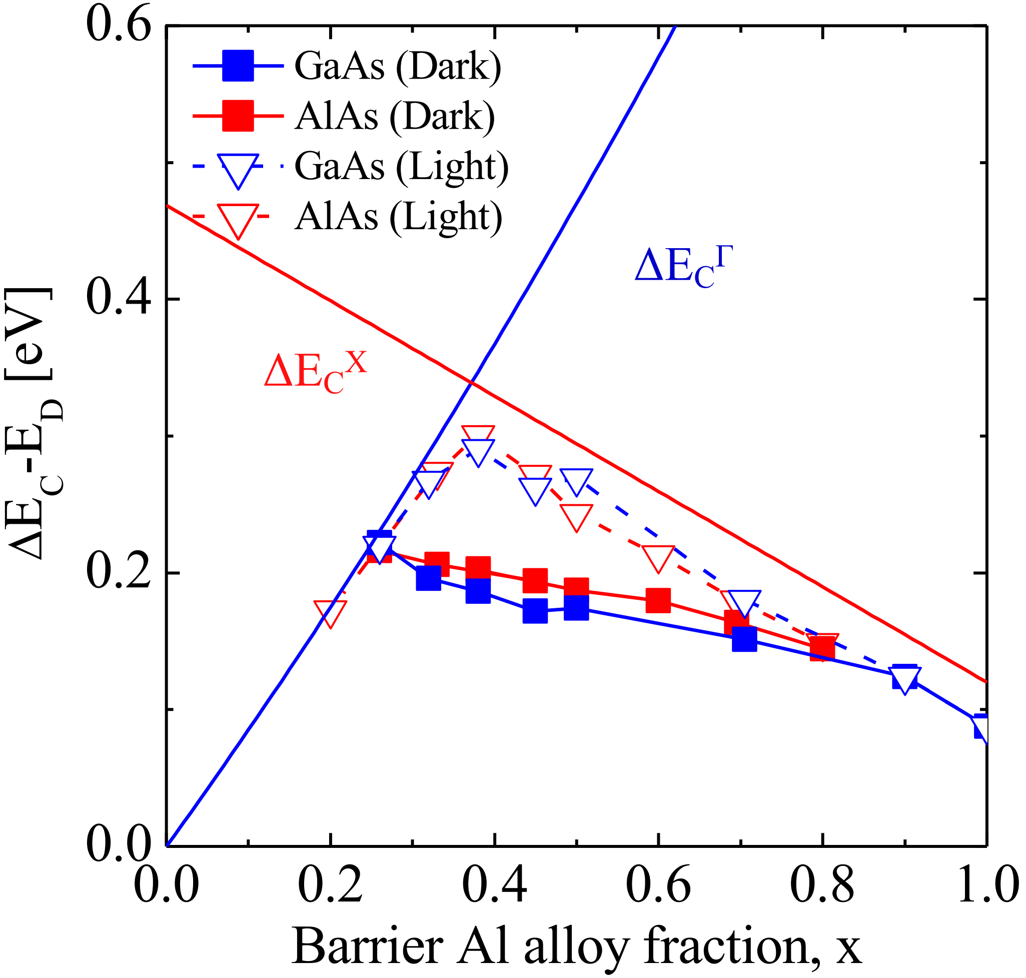


- Still large contribution from IR scattering
- Would also need growth optimization to reduce IR scattering

Outline

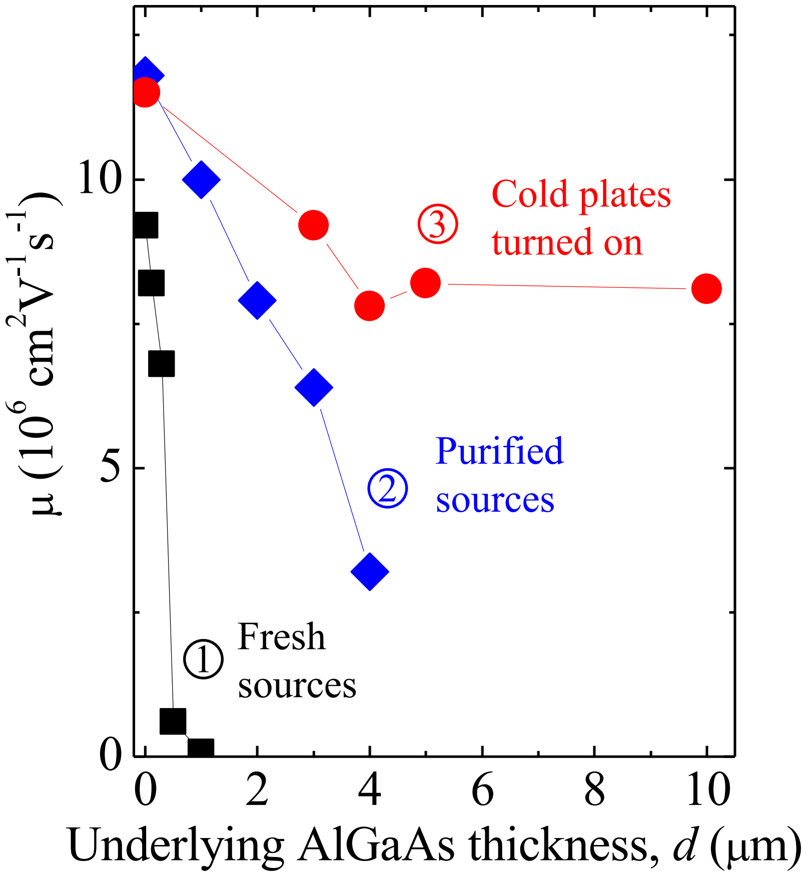
- Introduction
  - Clean 2DESs and the GaAs/AlAs materials group
- 2DESs in GaAs/AlAs quantum wells
  - Defining GaAs and AlAs 2DESs
  - Systematic impurity reduction
  - Record-quality AlAs and GaAs 2DESs
- Summary

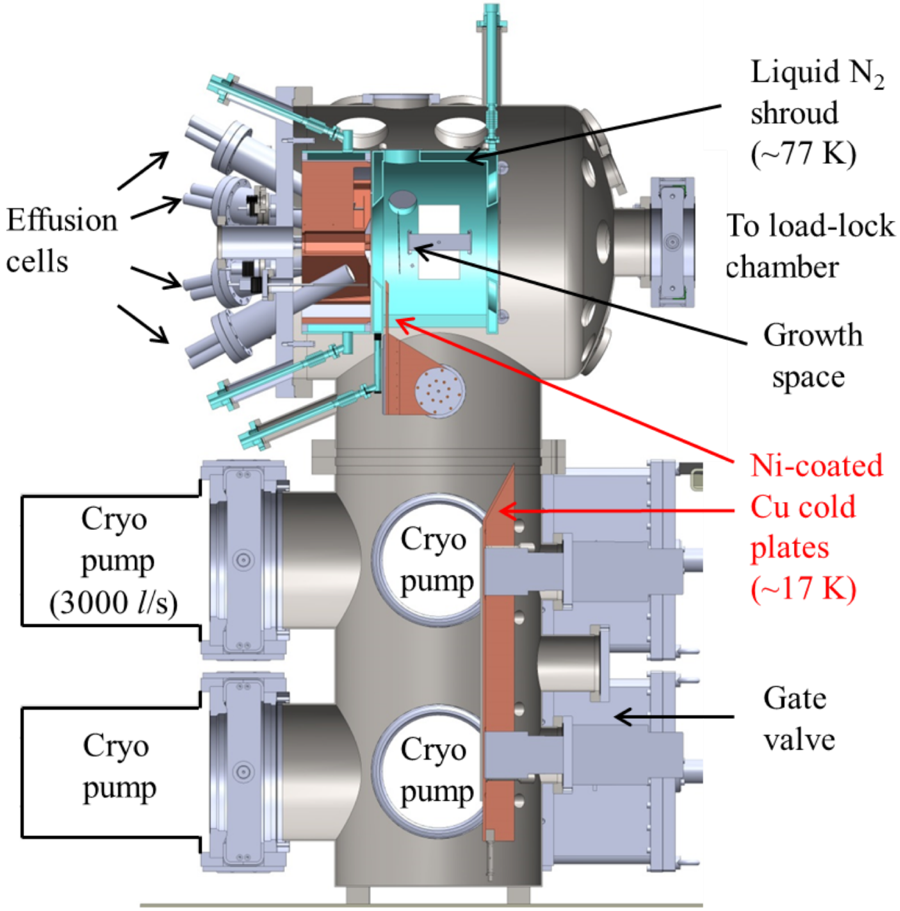
Summary



Y. J. Chung, Phys. Rev. Mater. **1**, 021002(R) (2017)

Summary

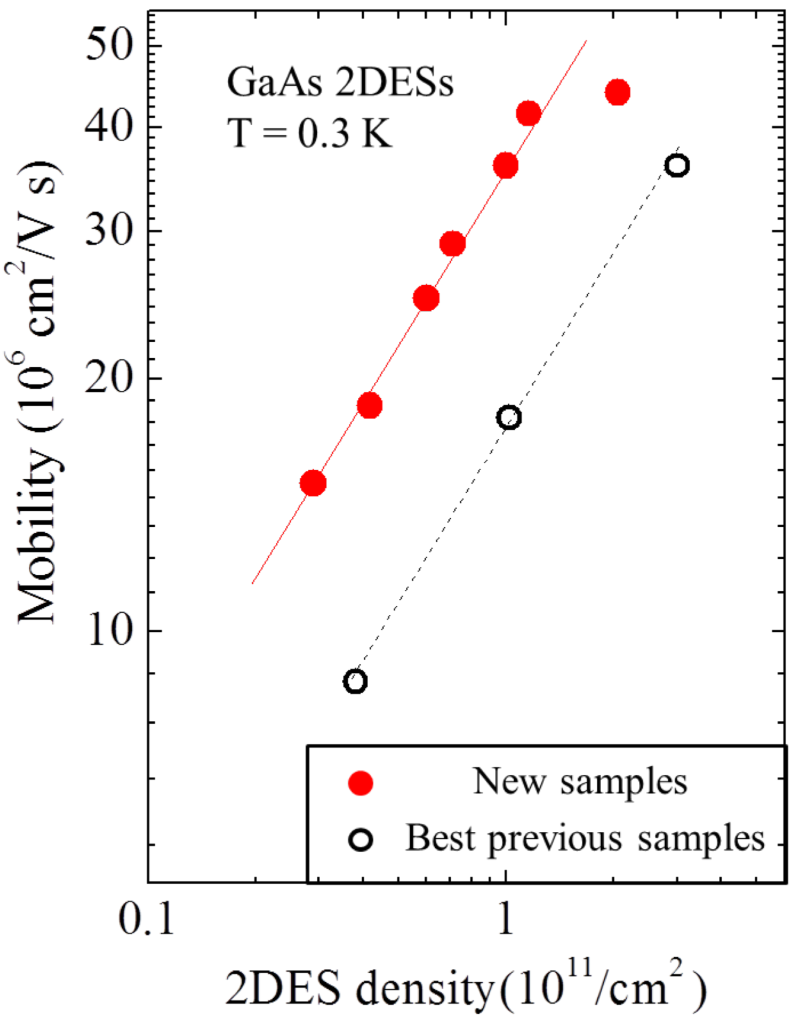


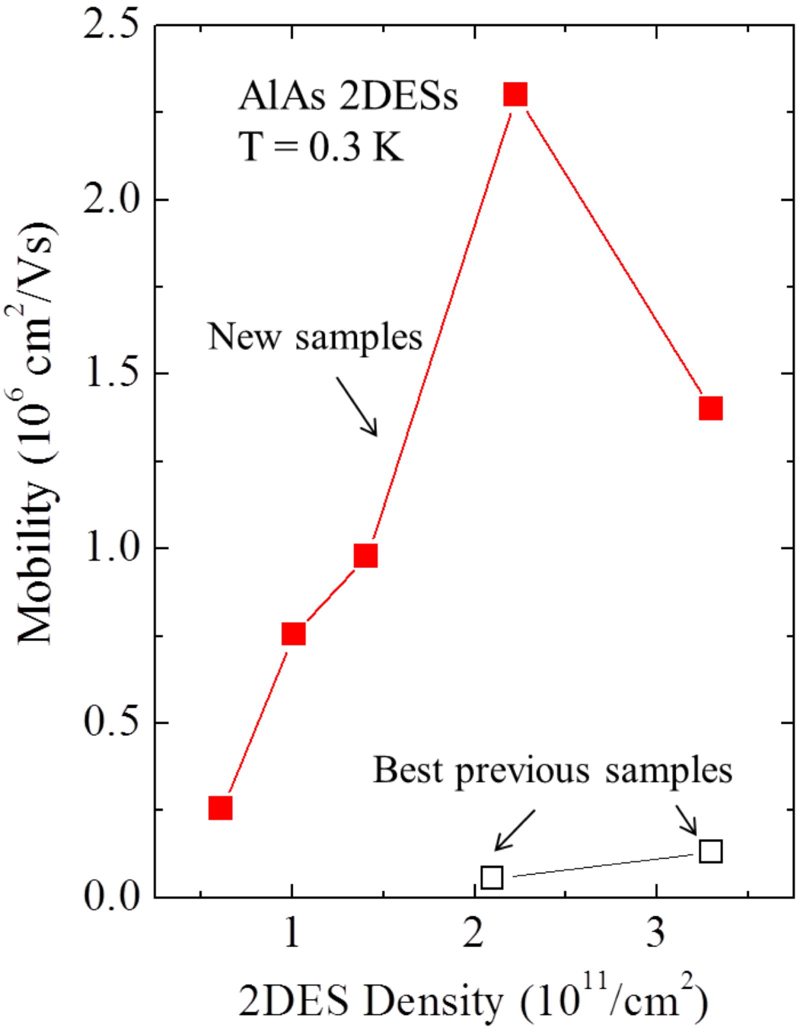


Y. J. Chung, Phys. Rev. Mater. **2**, 034006 (2018)

Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Summary

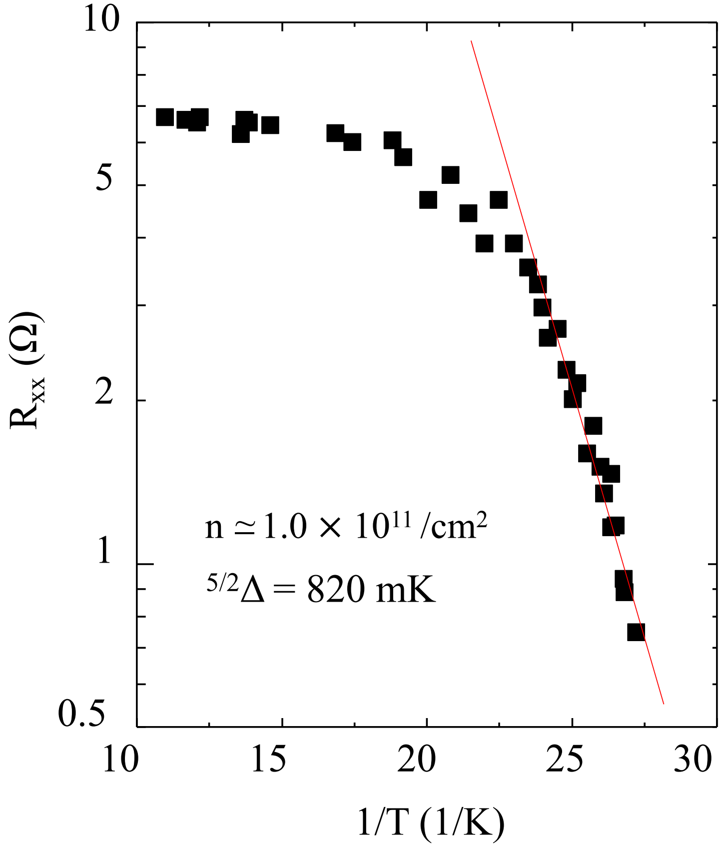


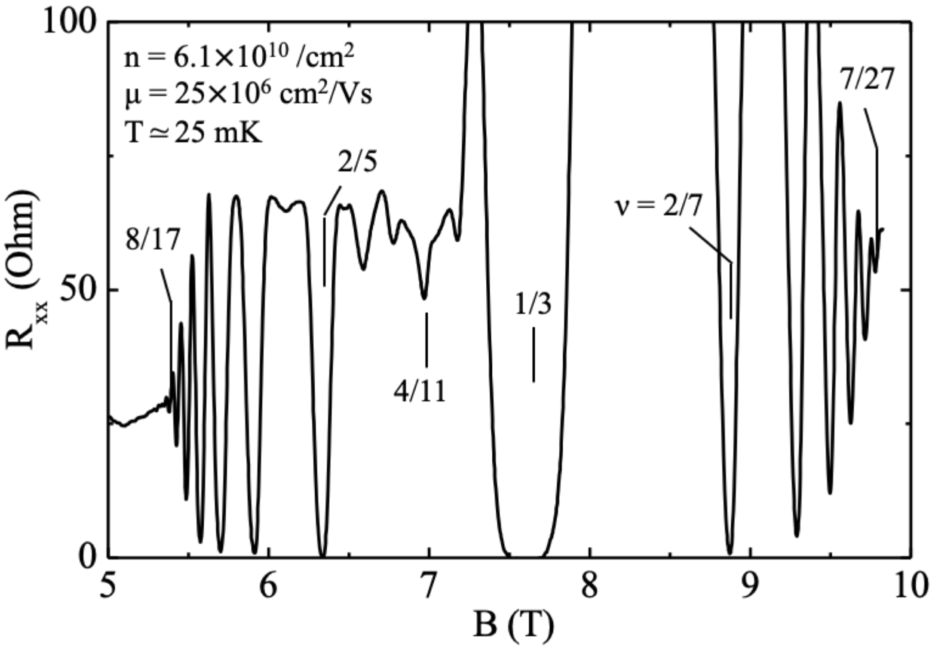


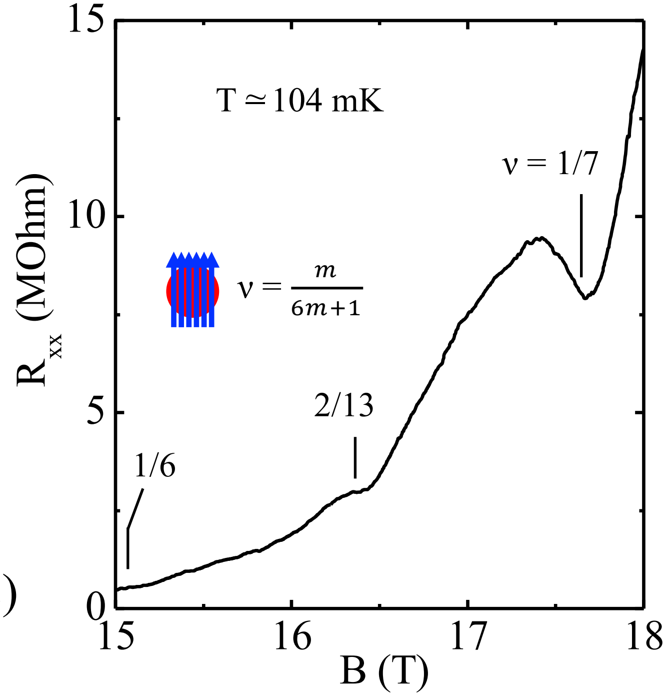
Y. J. Chung, Phys. Rev. Mater. **2**, 071001(R) (2018)

Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Summary



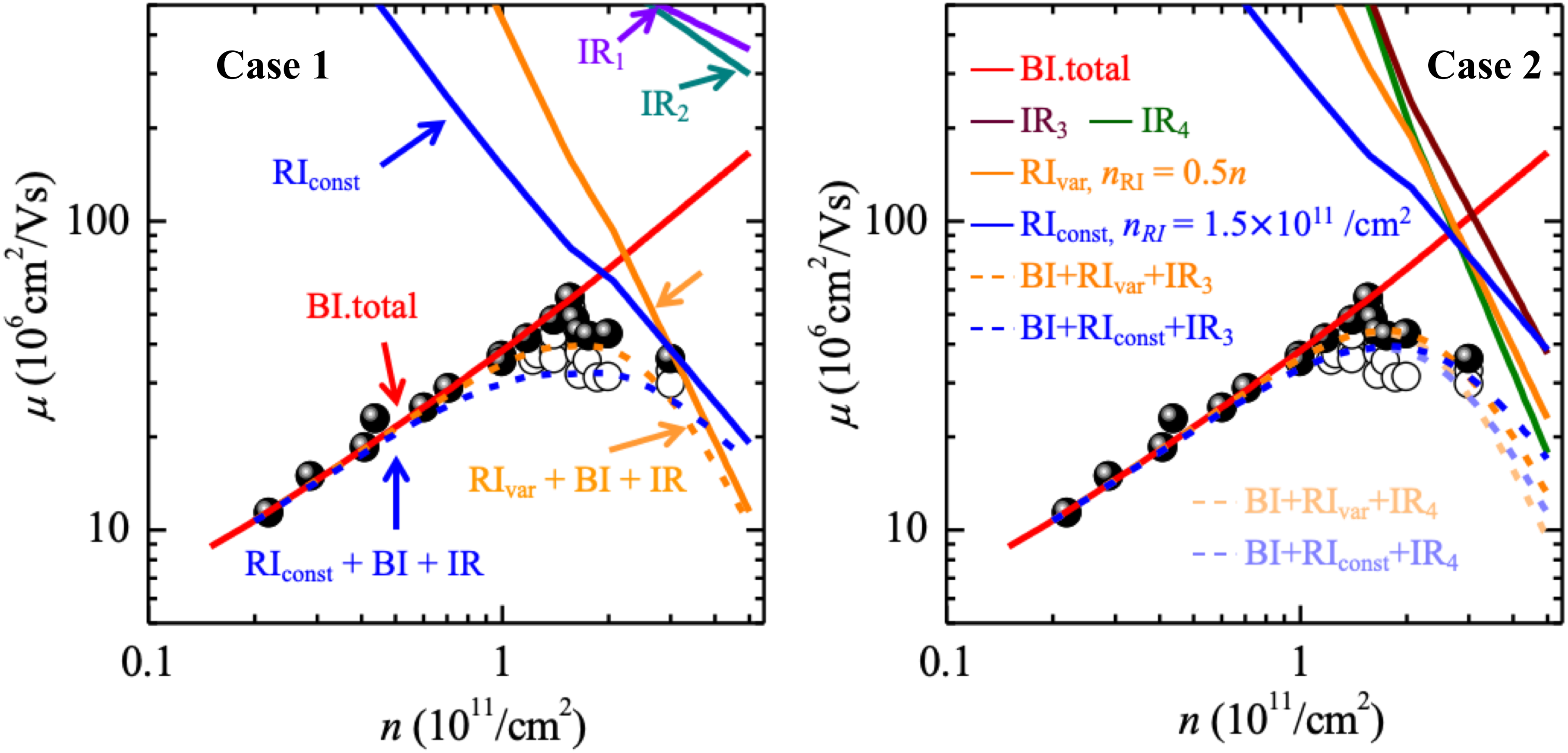




Y. J. Chung, Nat. Mater. **20**, 632 (2021)

Y. J. Chung, Phys. Rev. Lett. **128**, 026802 (2022)

Summary



Y. J. Chung, Phys. Rev. B **106**, 075134 (2022)

Thanks for your attention!