Negative Differential Conductivity of 2D Electron Gas System at High Magnetic Field

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Acknowledge:

- Cheng-Chung Chi, Chung-Yu Mou

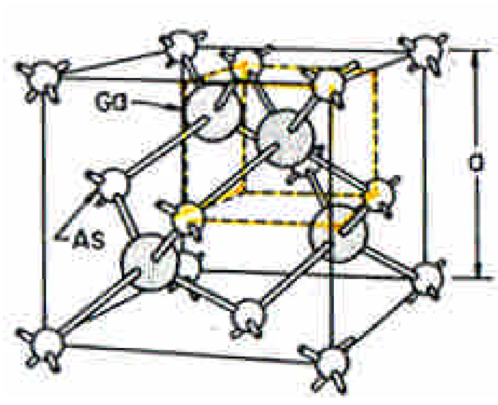
Ref: J. C. Chen*, Yuling Tsai, Yiping Lin, T. Ueda, S. Komiyama, *Phys. Rev. B*, **79**, 075308(2009).

Outline

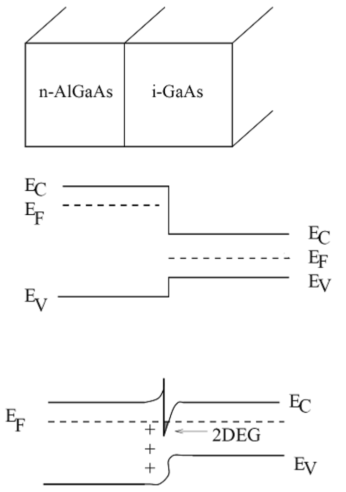
- **Introduction:**
  - Experimental system:
    Two-dimensional electron gas system (2DEG)
  - Integer Quantum Hall Effect (IQHE)
  - Negative differential conductivity (NDC)
- **Motivation:**
  - Microwave induced zero resistance states in 2DEG
  - NDC at high magnetic field
- **NDC of 2DEG at high magnetic field**
  - Measurement
  - Data analysis – Demonstration and consequence of NDC
  - Physical origin of NDC
- **Summary**

Experimental system: GaAs-AlGaAs heterostructure

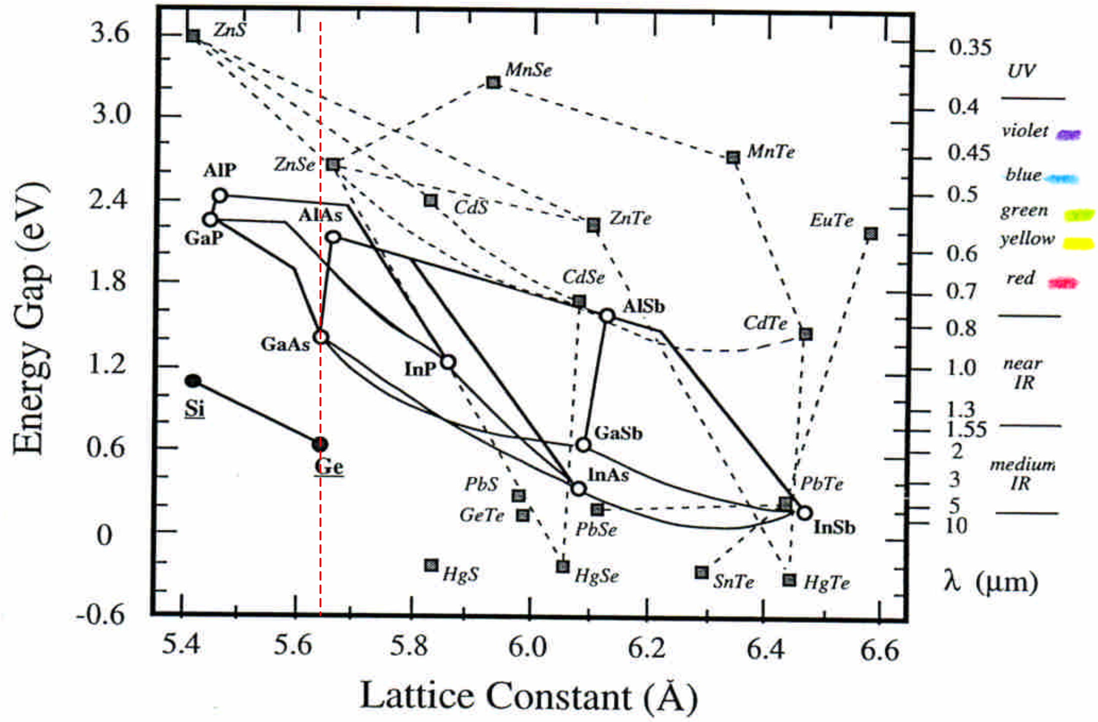
GaAs crystal structure



Heterostructurs / band engineering

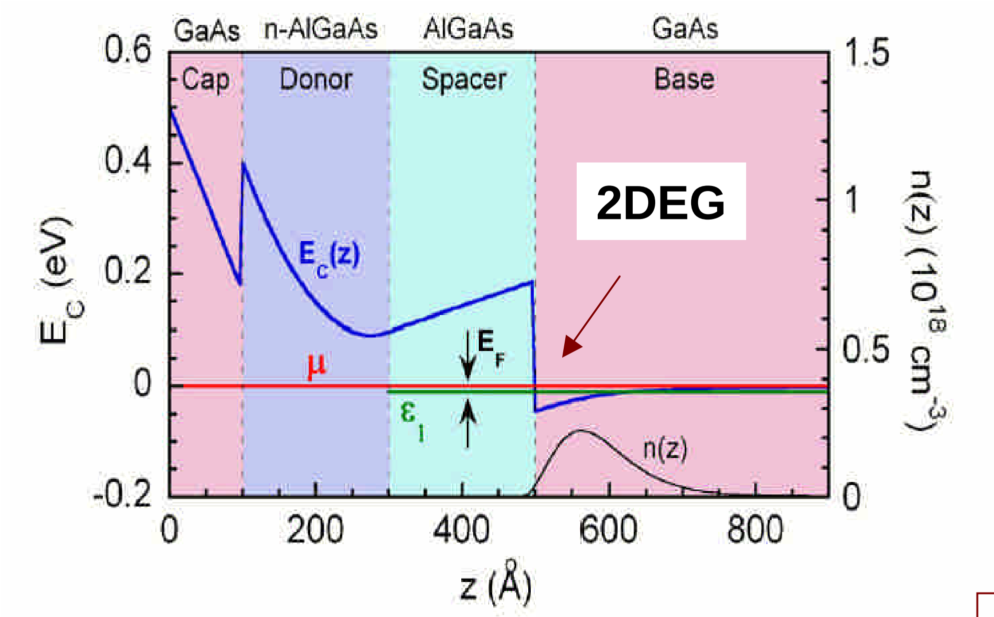


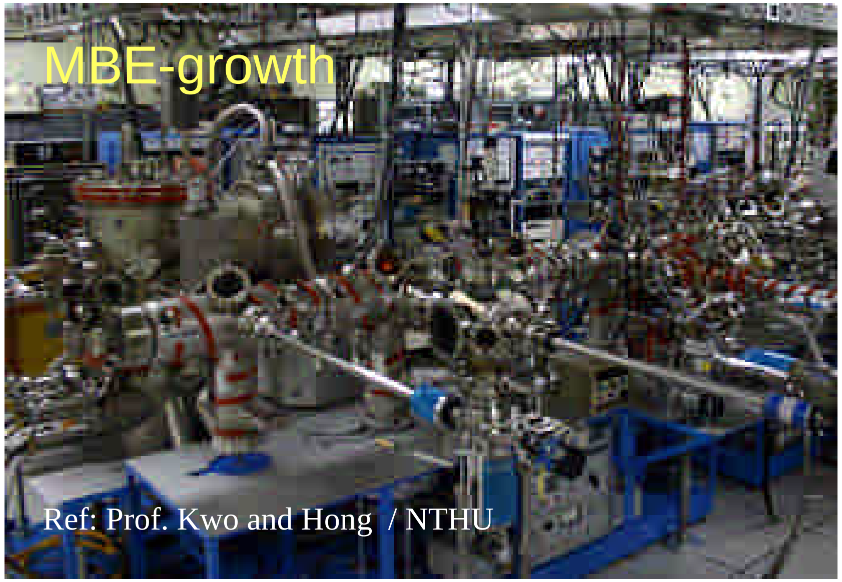
Bandgap energy & Lattice constant for elemental and binary compound semiconductors



	Lattice constant(Å)	Band gap (ev)		Effective mass	Lattice structure	Gap type
GaAs	5.653	1.52	1.43	0.067	Zinc-blende	Direct
AlAs	5.660	2.24	2.16	0.1		Indirect
$Al_xGa_{1-x}As$	Linear interpolation between alloy's constituents					x>0.35 indirect x<0.35 direct

Experimental system: Two dimensional electron gas (2DEG)





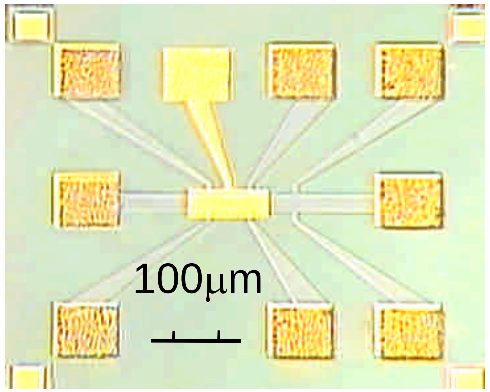
2DEG is formed at the interface between GaAs & AlGaAs

Electronic properties of 2DEG

- Carrier density: n_s=1-4×10^{11} 1/cm^2
- Fermi wavelength: λ_F=40nm
- Electron mobility: μ_e=10^5-10^6cm^2/Vs
- Mean free path: l =10^3-10^4nm
- Phase coherence length: l_ϕ=*200-nm*

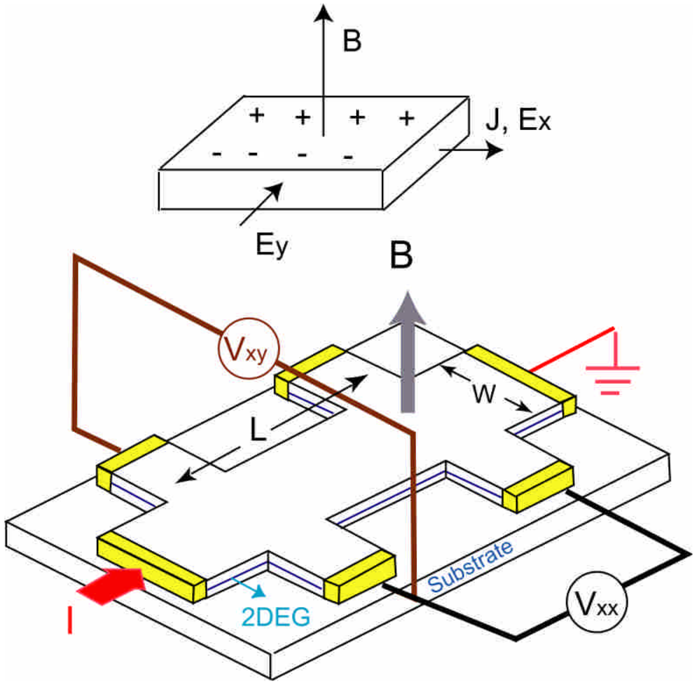
Device Fabrication:

- Photolithography
- Etching // Mesa
- Ohmic contacts /Alloying
- Metallization



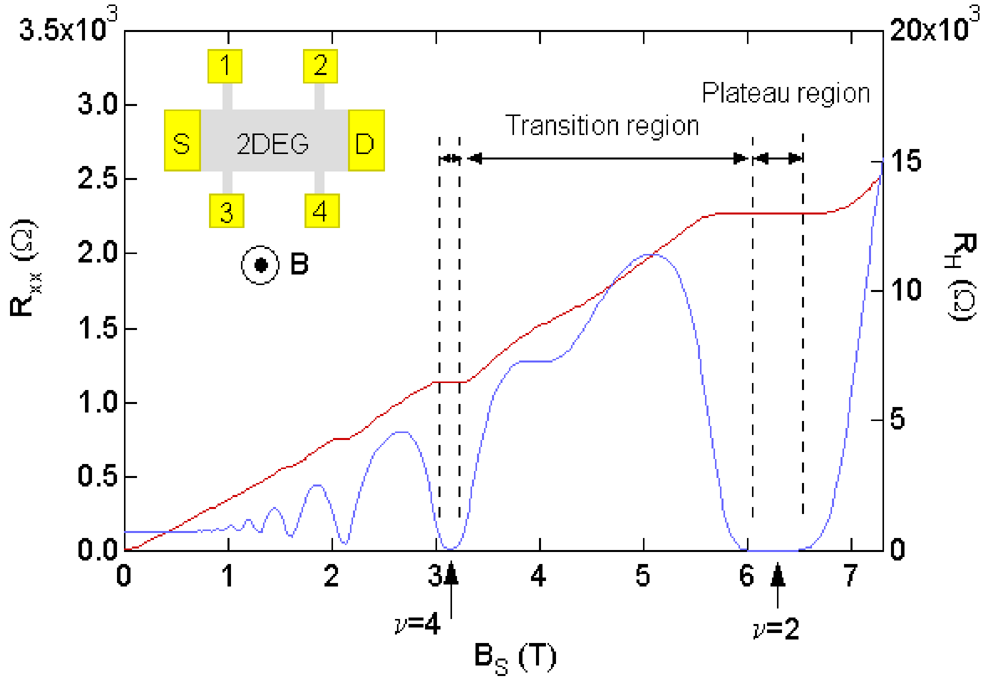
Integer Quantum Hall effect (IQHE)

Hall effect



- $E_x = \rho_{xx} J_x,\ E_y = \rho_{xy} J_x$
- $R_{xx} = \dfrac{V_{xx}}{I},\ R_{xy} = \dfrac{V_{xy}}{I}$
- $\rho_{xx} = \dfrac{V_{xx}}{I}\dfrac{W}{L}, \rho_{xy} = \dfrac{V_{xy}}{I}$
- Hall angle : $\Psi = \tan^{-1}(E_y / E_x)$

IQHE experiment



- Temp: 4.2K
- GaAs/AlGaAs 2DEG
- $\dfrac{h}{e^2} = 25.81k\Omega$

ν : Integer

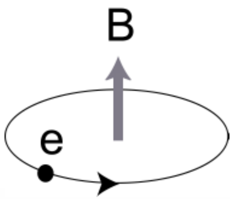
$$\begin{cases} R_{xx} = 0 \\ R_{xy} = \dfrac{1}{\nu}\dfrac{h}{e^2} \end{cases}$$

Integer Quantum Hall effect

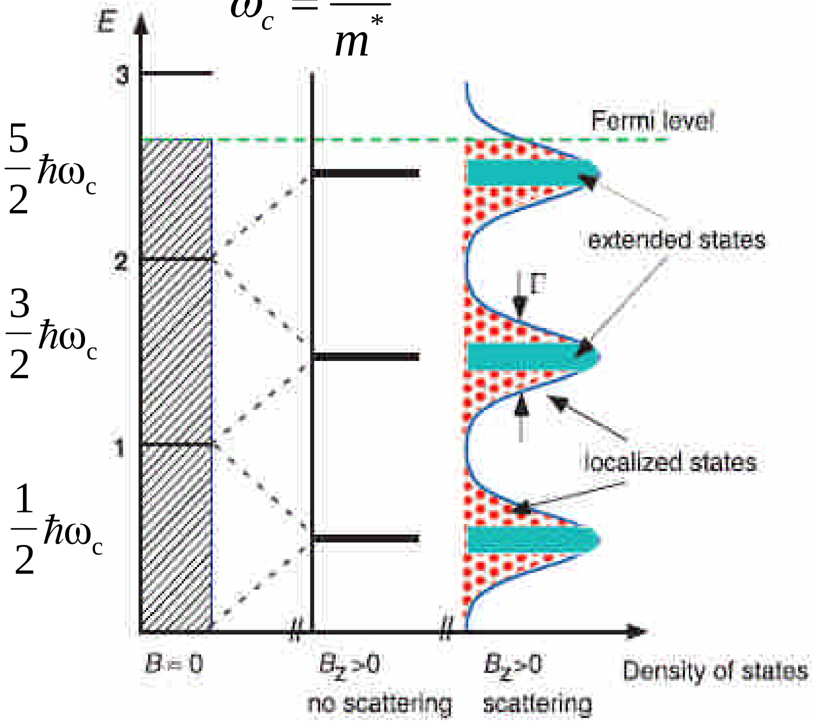
Landau levels
(single particle picture)

$$[E_c + \frac{i\hbar\nabla + eA^2}{2m^*} + U(r)]\ \psi(r) = E\psi(r)$$

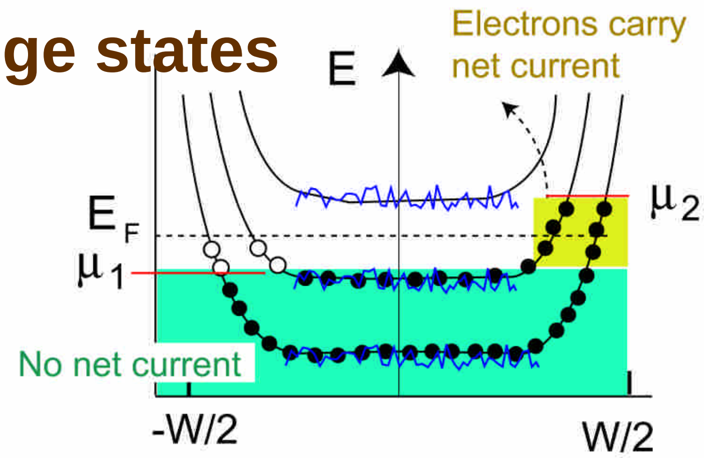
$$\Rightarrow E_n = E_s + (n + \frac{1}{2})\hbar\omega_c$$

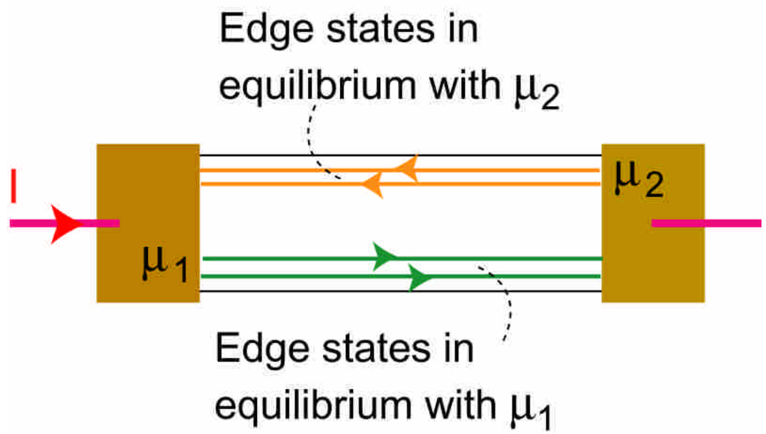


$$\omega_c = \frac{eB}{m^*}$$



Edge states

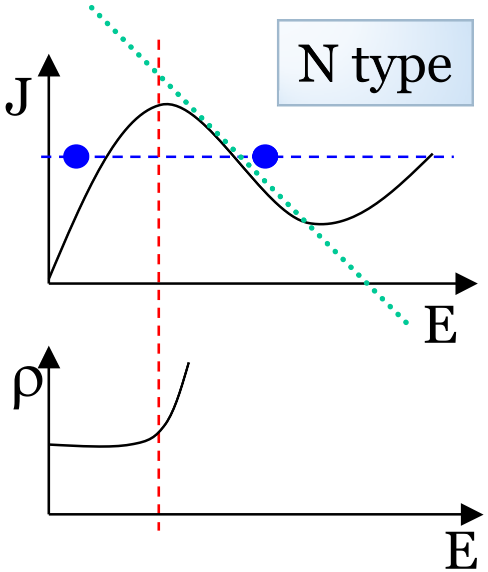


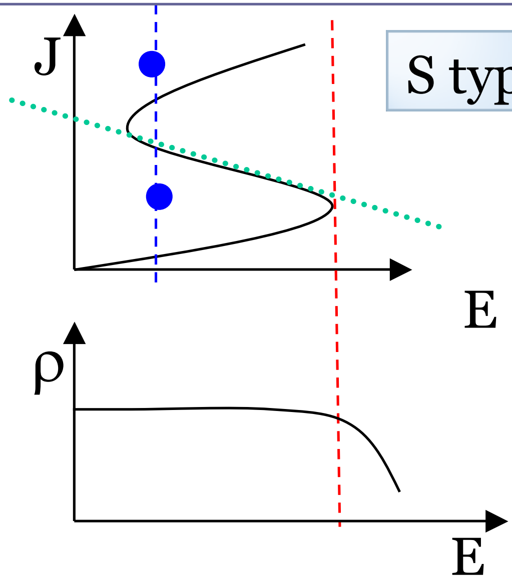


$$R_{xy} = \frac{V_{xx}}{I} = 0 \quad \text{No scattering}$$

$$R_{xy} = \frac{V_{xy}}{I} = \frac{(\mu_1 - \mu_2)/e}{\frac{2e}{h}\nu(\mu_1 - \mu_2)} = \frac{h}{2e^2\nu}$$

Negative differential conductivity (NDC) in a bulk semiconductor





J-E relation $\boldsymbol{J} = \boldsymbol{\sigma E}$

- Ohm Law: Linear
- Multivalueness in J-E relation
- Multivalley in Band
- NDC $\rightarrow$ unstable system

(Ref. S.M. Sze, Physics of Semiconductor Devices, 2nd, Ch11, p.639)

$$\frac{\partial n}{\partial t} + \frac{1}{q}\frac{\partial J}{\partial x} = 0$$

$$\frac{\partial E}{\partial x} = \frac{q(n-n_0)}{\varepsilon_S}$$

$$J = \sigma E - qD\frac{\partial n}{\partial x}$$

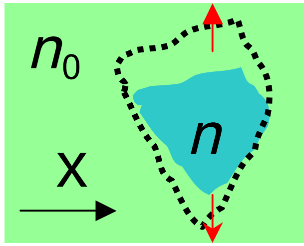
$$\frac{\partial n}{\partial t} - \sigma\frac{n-n_0}{\varepsilon_s} - D\frac{\partial^2 n}{\partial x^2} = 0$$

NDC$\Rightarrow$ space-charge growth

$\Rightarrow$ spatial response

Restrict spatial distribution

$$n - n_0 = (n-n_0)_{x=0}\exp(-x/L_D);\ L_D = \sqrt{\frac{kT\varepsilon_s}{q^2 n_0}}$$

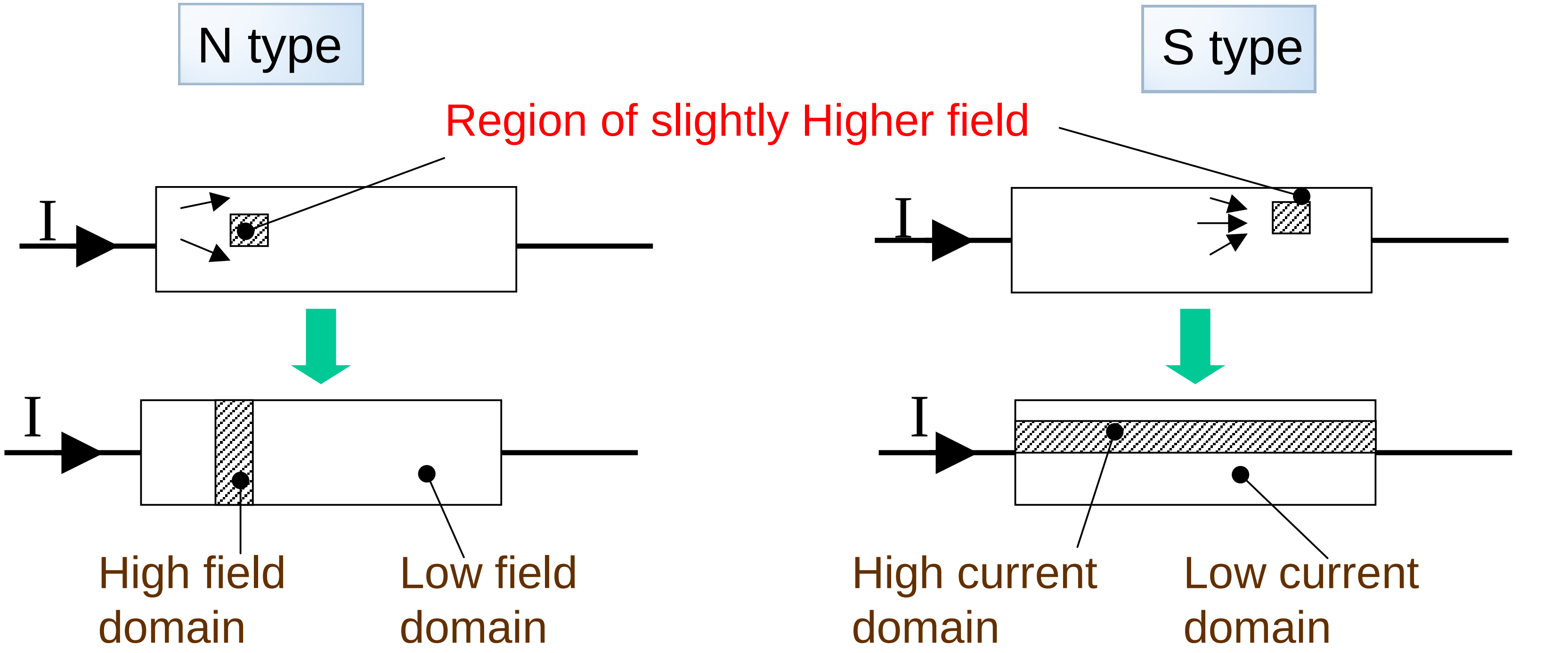


$\Rightarrow$ temporal response

$$n - n_0 = (n-n_0)_{t=0}\exp(-t/\tau_R)\ ;\tau_R \equiv \frac{\varepsilon_s}{\sigma}$$

$$\sigma < 0 \Rightarrow n - n_0 \uparrow$$

Consequence of Bulk NDC



(Ref. S.M. Sze, Physics of Semiconductor Devices, 2nd, Ch11, p.639)

To reach the stability $\Rightarrow$ system becomes electrically heterogeneous.

What happens if the system is in a strong magnetic field?

Motivation: Microwave induced zero resistance states in 2DEG

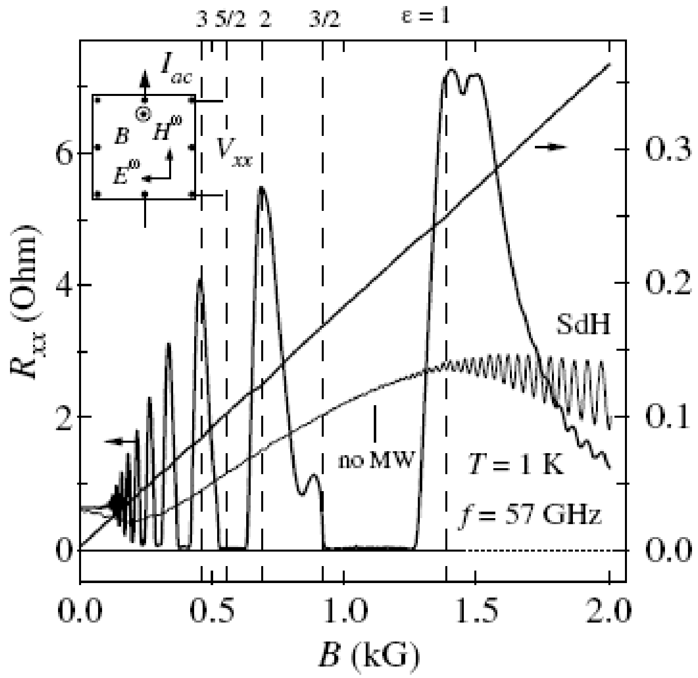
- Zero Resistance
  - Instability initiated by microwave irradiation
  - Theories based on the framework of negative differential conductivity (NDC) in bulk

Apply MW

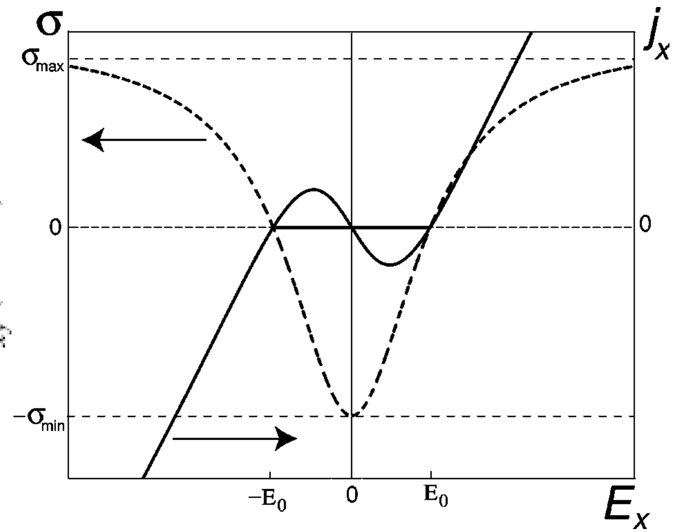
$R_{XX} \rightarrow 0$

But

$R_H \neq h/2e^2(1/\nu)$

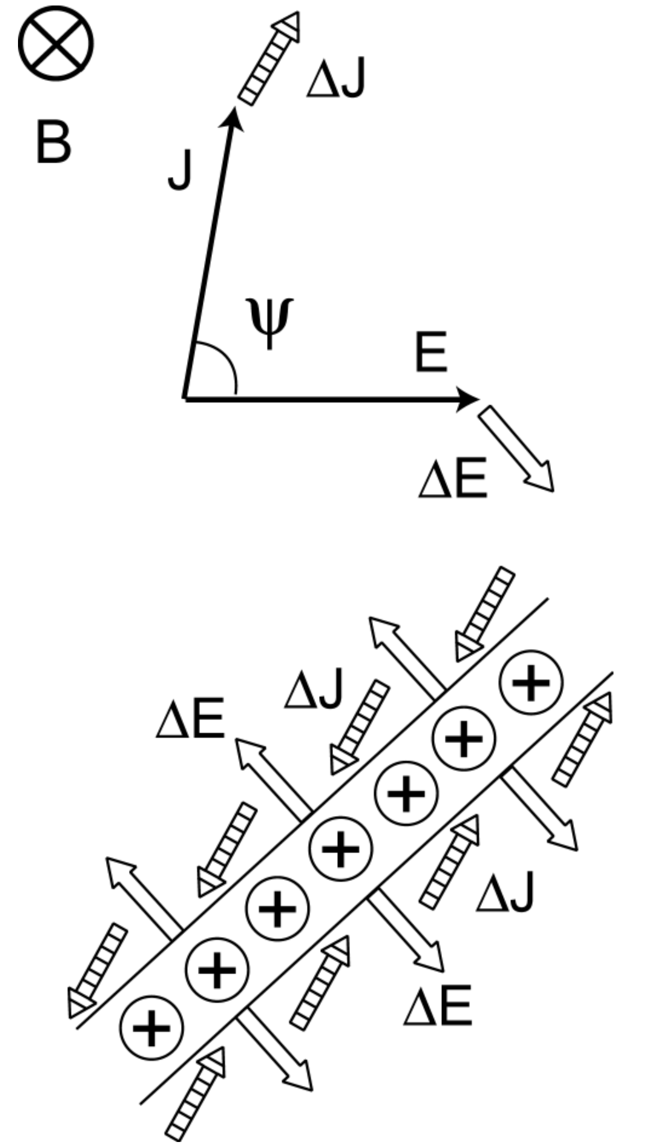


(PRL **90**, 046807, 2003)



(PRB **67**, 241303(R) 2003)

Motivation: Physical picture of NDC at high magnetic Field



Ref: Tatsumi Kurosawa, J. Phys. Soc Japan **36**,491(1974)

Consider a homogeneous system with current **J**, electric field **E** and magnetic field **H**. $\mathbf{E} \perp \mathbf{H} // \mathbf{z}$

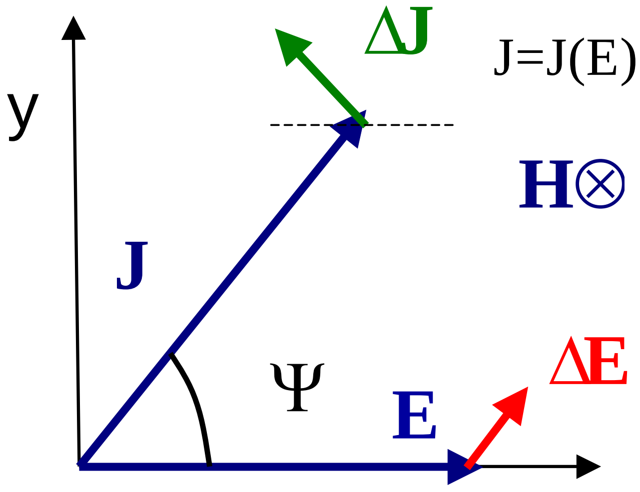
Electrical instability

- Hall angle ψ large at high B field
- Due to the growth of space charges
- Criterion:

$$\Delta\mathbf{E} \cdot \Delta\mathbf{J} < 0$$

If the condition is fulfilled , the additional current flows into the space-charge sheet and builds it up

Conditions of current instability : Kurosawa's theory



$J=J(E)\ ,\Psi=\Psi(E)$

$$\Rightarrow \mathbf{J} = \begin{pmatrix} \sigma^{d}_{xx} & (\frac{\sigma^{d}_{xy}+\sigma^{d}_{yx}}{2}) \\ (\frac{\sigma^{d}_{xy}+\sigma^{d}_{yx}}{2}) & \sigma^{d}_{yy} \end{pmatrix} \mathbf{E} = \sigma^{d}_{symm}\mathbf{E}$$

To have negative eigenvalue(s)

$$\Rightarrow \quad |\boldsymbol{\sigma}^{d}_{symm}| < 0$$

i.e. satisfy $\quad \Delta\mathbf{E}\cdot\Delta\mathbf{J} < 0$

$J = J(E,H)$,

$$\Delta J_i = \sum_j \frac{\partial J_i}{\partial E_j}\Delta E_j = \sum_j \sigma^{d}_{ij}\Delta E_j$$

From symmetric consideration

$$\sigma^{d}_{xz} = \sigma^{d}_{yz} = \sigma^{d}_{zx} = \sigma^{d}_{zy} = 0$$

$$\sigma^{d}_{xx} = \frac{\partial J_x}{\partial E_x} = \frac{dJ}{dE}\cos\Psi - J\sin\Psi\frac{d\Psi}{dE}$$

$$\sigma^{d}_{yx} = \frac{\partial J_y}{\partial E_x} = \frac{dJ}{dE}\sin\Psi + J\cos\Psi\frac{d\Psi}{dE}$$

$$\sigma^{d}_{xy} = \frac{\partial J_x}{\partial E_y} = -\frac{J}{E}\sin\Psi$$

$$\sigma^{d}_{yy} = \frac{\partial J_y}{\partial E_y} = \frac{J}{E}\cos\Psi$$

Conditions of current instability : Kurosawa's theory

Define a parameter D: $D \propto Det(\sigma^{d}_{symm})$

$$D = \underbrace{\beta^2 \tan^2 \Psi}_{(1)} + 2\alpha(2-\beta)\tan\Psi + \alpha^2 - 4(1-\beta)$$

The condition for instability: D > 0

When $\Psi \to \pi/2$
$\Rightarrow$ (1) is predominate
$\Rightarrow$ D > 0 as long as $\beta \neq 0$

$$\Delta \boldsymbol{E} \bullet \Delta \boldsymbol{J} < 0$$
$$\Rightarrow \quad |\boldsymbol{\sigma}^{d}_{symm}| < 0$$

$$\alpha \equiv E \frac{d\Psi}{dE}$$

$$\beta \equiv 1 - \frac{E}{J}\frac{dJ}{dE}$$

Nonlinearity of J(E)

Key : Even a weak nonlinearity in **J-E** can cause the instability when **H** is strong enough !

NDC and IQHE

IQH states : $R_{xx}=0$, $R_{xy}=h/2e^2(1/\nu)$

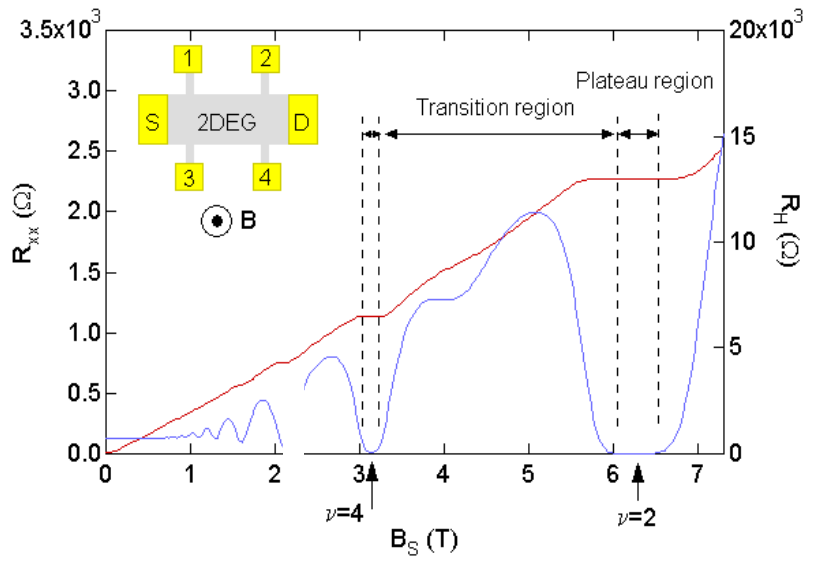
$$E=[(\frac{V_{xx}}{d})^2+(\frac{V_{xx}}{w})^2]^{1/2},\ J=\frac{I_{SD}}{w}$$

$$\Psi=\tan^{-1}(\frac{E_y}{E_x})\cong\tan^{-1}(\frac{V_{xy}}{V_{xx}}\frac{d}{w})$$

$$\Rightarrow V_{xx}\to 0, \Psi\to\pi/2$$

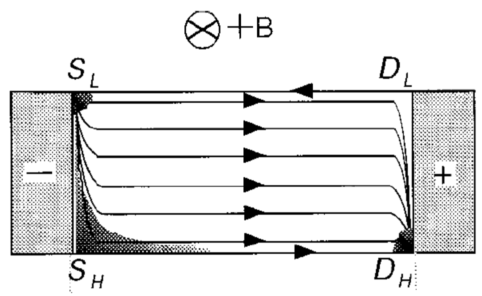
Current instability rises easily ! ?
QHE breakdown ?

IQHE



Problem: inhomogeneous E-filed distribution inside the sample in IQH regime

Solution: rising the lattice temperatures



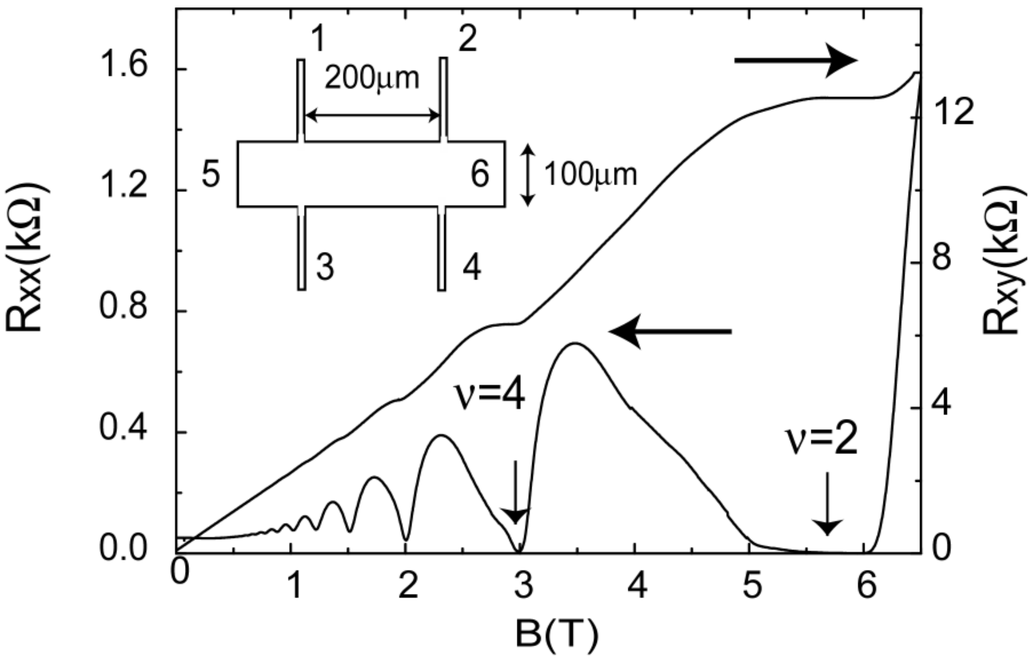
Ref: Y. Kawano, etc. , Phys. Rev. B **61**, 2931(2000)

NDC in 2D Electron Gas System

Sample 1

$GaAs/Al_{0.3}Ga_{0.6}As$ heterostructure

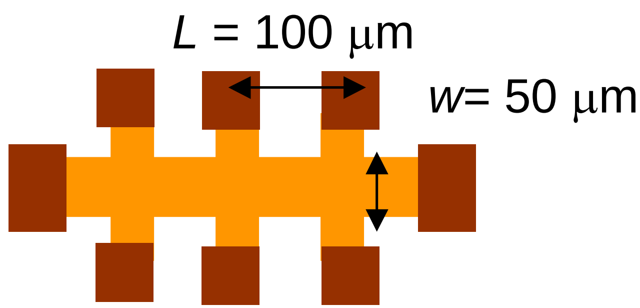
$N_s = 3.0\times10^{11}$ cm^{-2}
$\mu = 0.8\times10^{6}$ cm^2/V·s



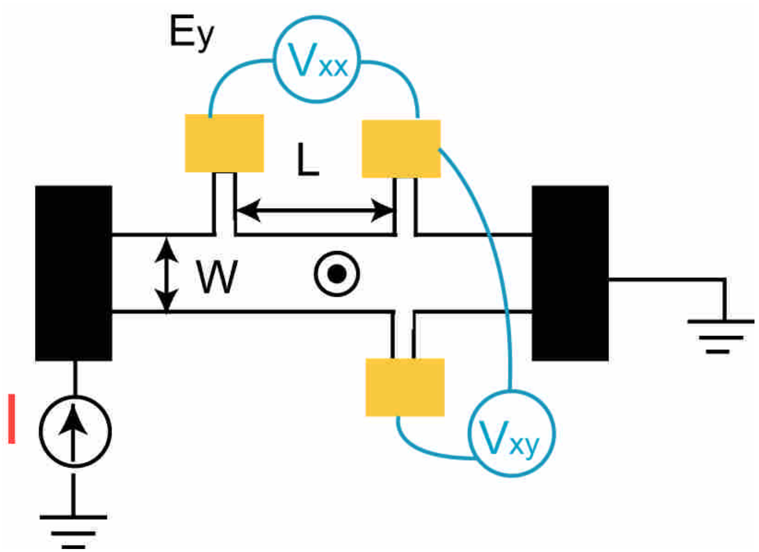
Sample 2

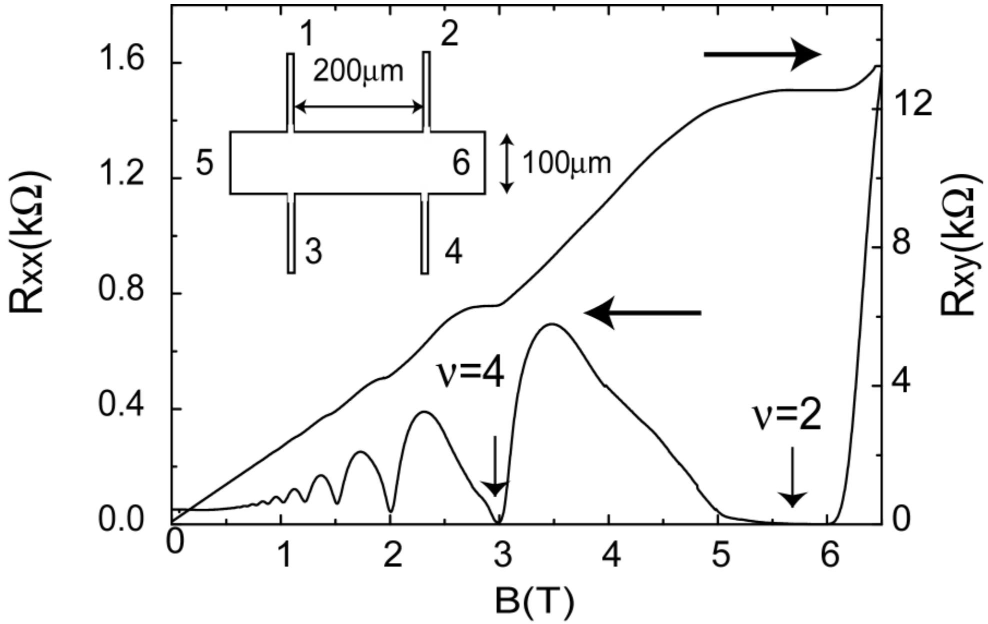
$GaAs/Al_{0.3}Ga_{0.6}As$ heterostructure

$N_s = 3.8\times10^{11}$ cm^{-2}
$\mu = 0.45\times10^{6}$ cm^2/V·s



Match Experiment with Theory





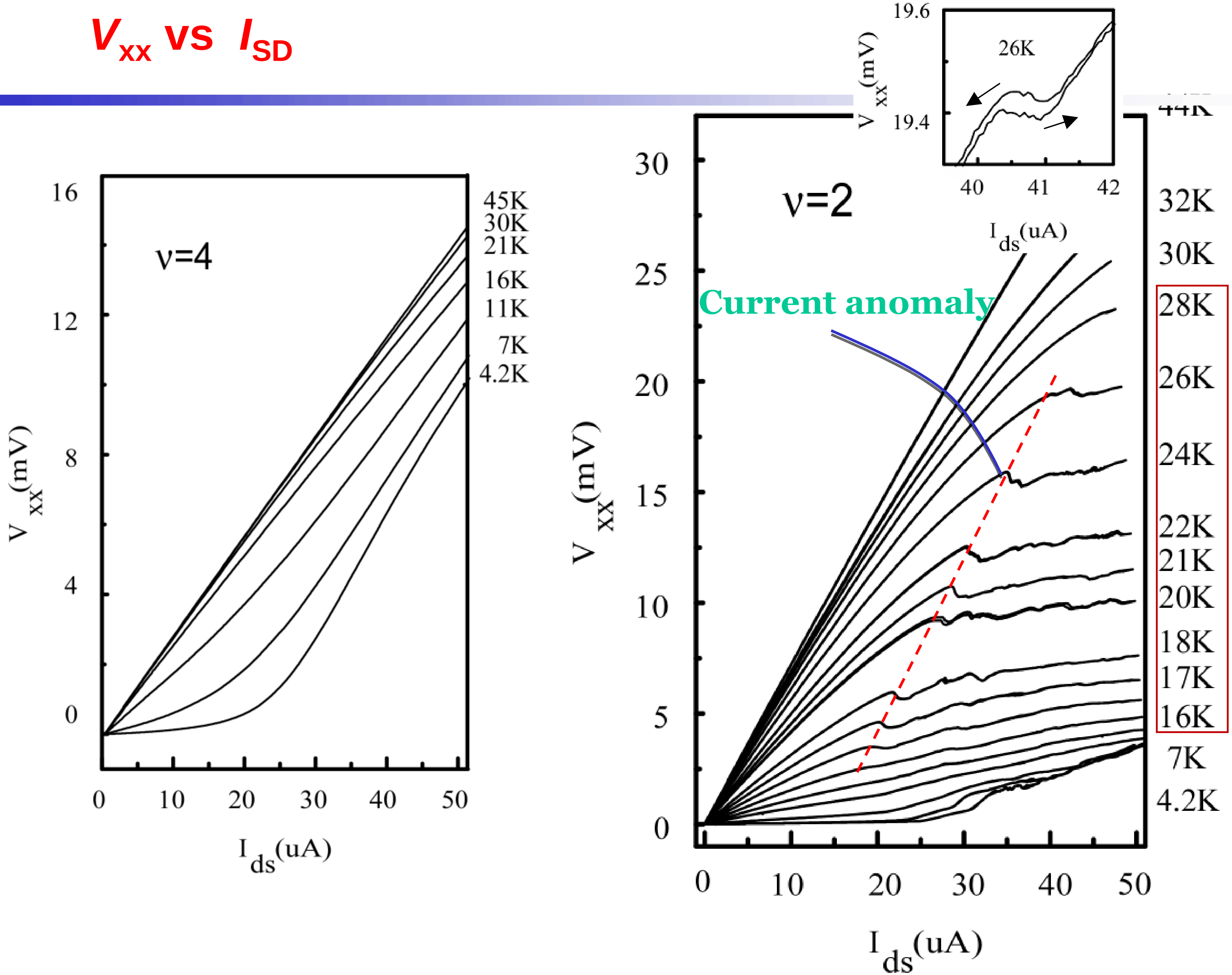
$$\boldsymbol{E} = [(\frac{\boldsymbol{V}_{xx}}{\boldsymbol{L}})^2 + (\frac{\boldsymbol{V}_{xy}}{\boldsymbol{W}})^2]^{1/2}$$

$$\boldsymbol{J} = \frac{\boldsymbol{I}_{SD}}{\boldsymbol{W}}$$

$$\Psi = \tan^{-1}(\frac{\boldsymbol{V}_{xy}}{\boldsymbol{V}_{xx}}\frac{\boldsymbol{L}}{\boldsymbol{W}})$$

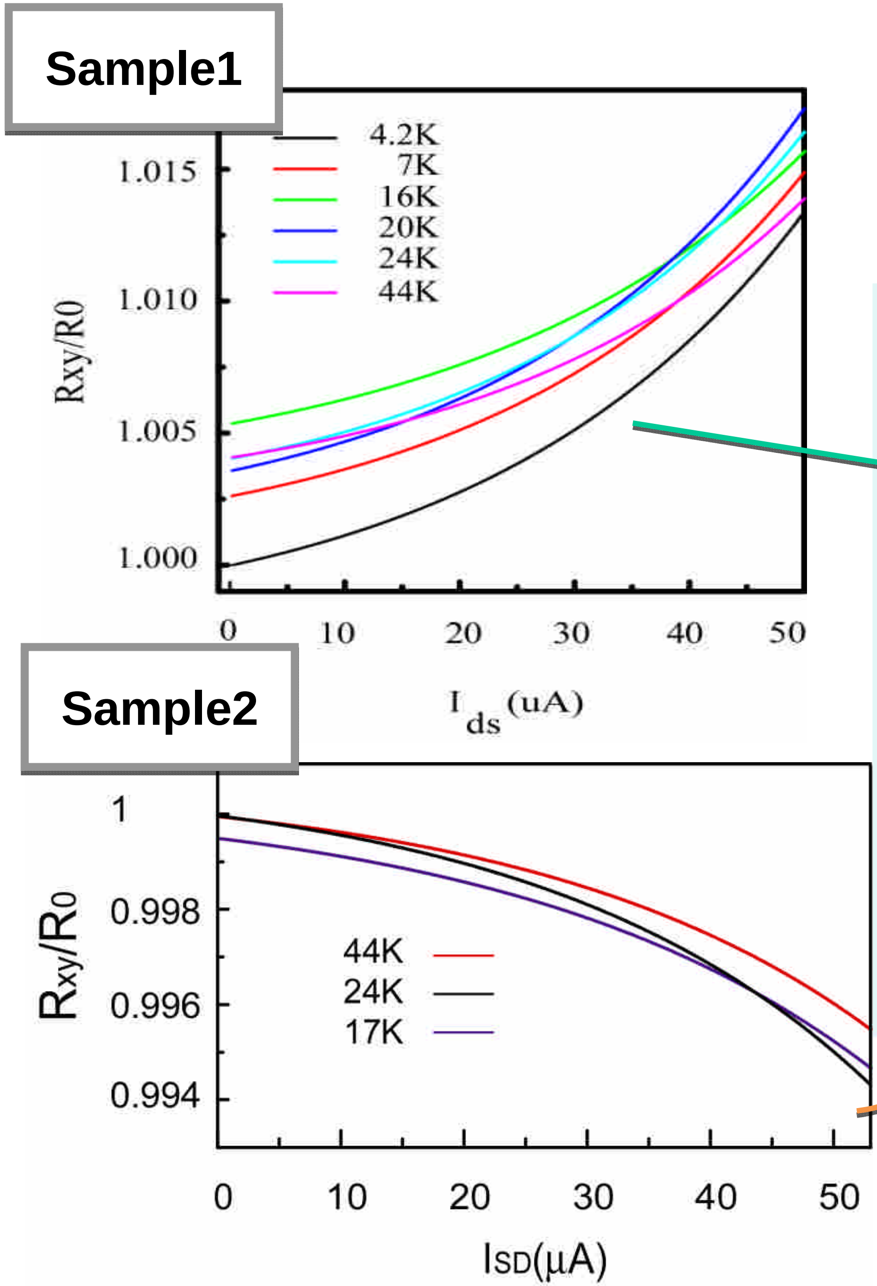
$$\Rightarrow \begin{cases} \alpha \equiv E\dfrac{d\Psi}{dE} \quad \& \quad \beta \equiv 1 - \dfrac{E}{J}\dfrac{dJ}{dE} \\ D = \beta^2 \tan^2\Psi + 2\alpha(2-\beta)\tan\Psi + \alpha^2 - 4(1-\beta) \end{cases}$$

V_{xx} vs I_{SD}

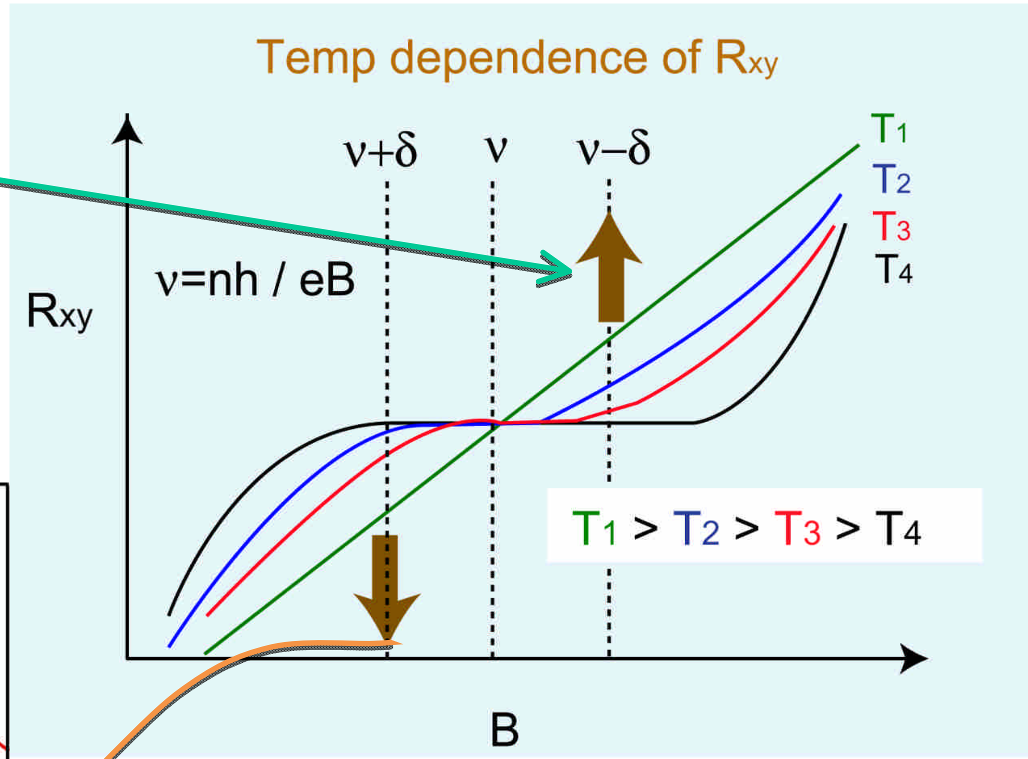


ν=4
45K
30K
21K
16K
11K
7K
4.2K
V_{xx}(mV)
I_{ds}(uA)
ν=2
Current anomaly
26K
V_{xx}(mV)
I_{ds}(uA)
32K
30K
28K
26K
24K
22K
21K
20K
18K
17K
16K
7K
4.2K
V_{xx}(mV)
I_{ds}(uA)

V_{xy} vs I_{SD}



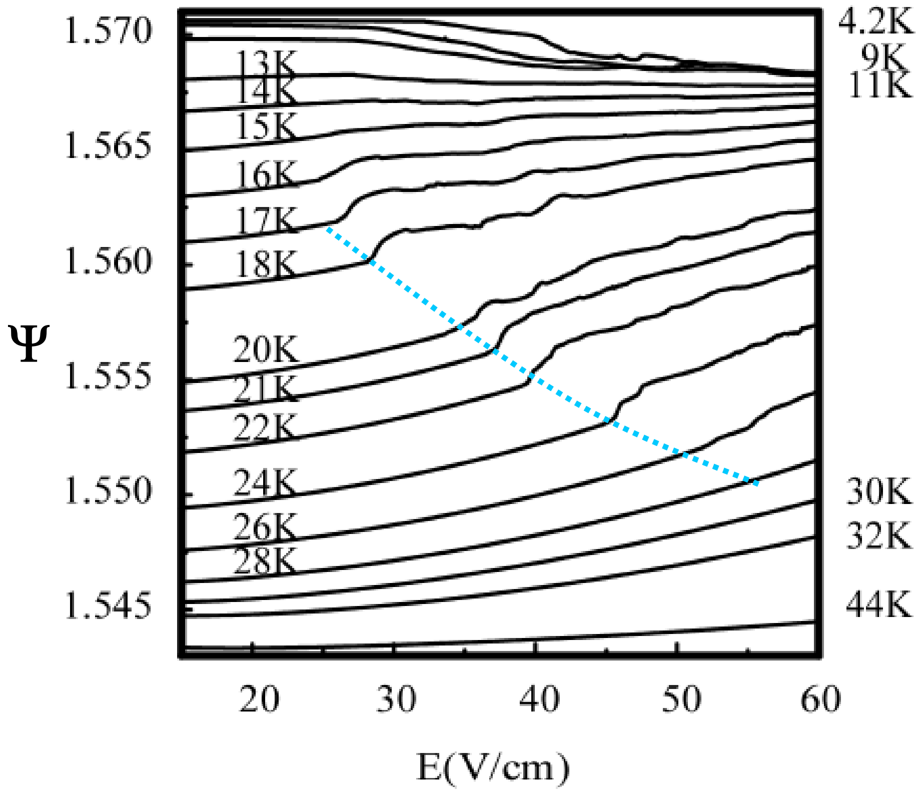
No current anomaly !

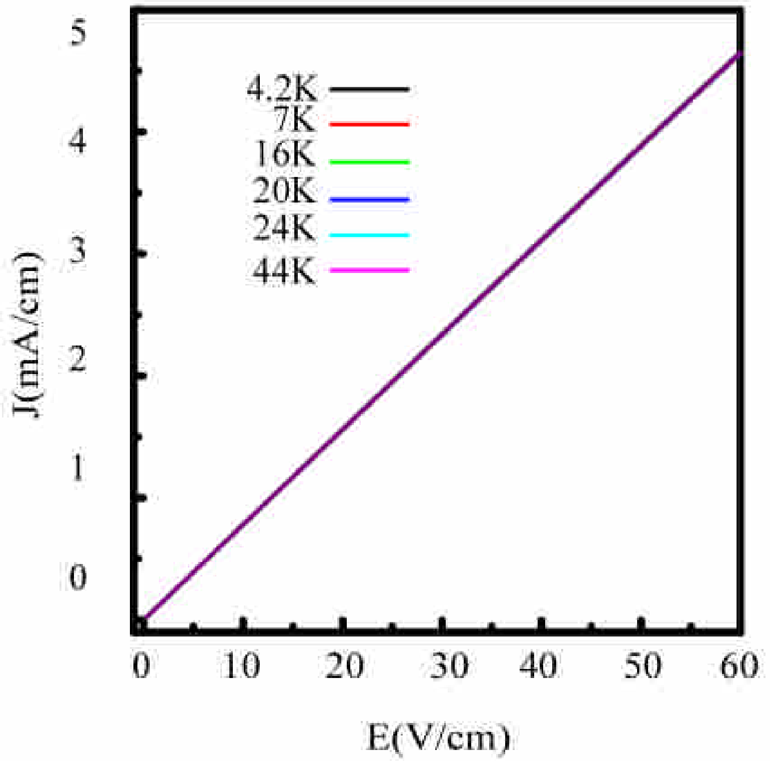


$I_{DS} \uparrow \Rightarrow$ Electron heating T$\uparrow$

J & Ψ as Function of E

$$E = [(\frac{V_{xx}}{L})^2 + (\frac{V_{xy}}{w})^2]^{1/2} \quad ; \quad J = \frac{I_{SD}}{w}; \quad \Psi = \tan^{-1}(\frac{V_{xy}}{V_{xx}}\frac{L}{w})$$





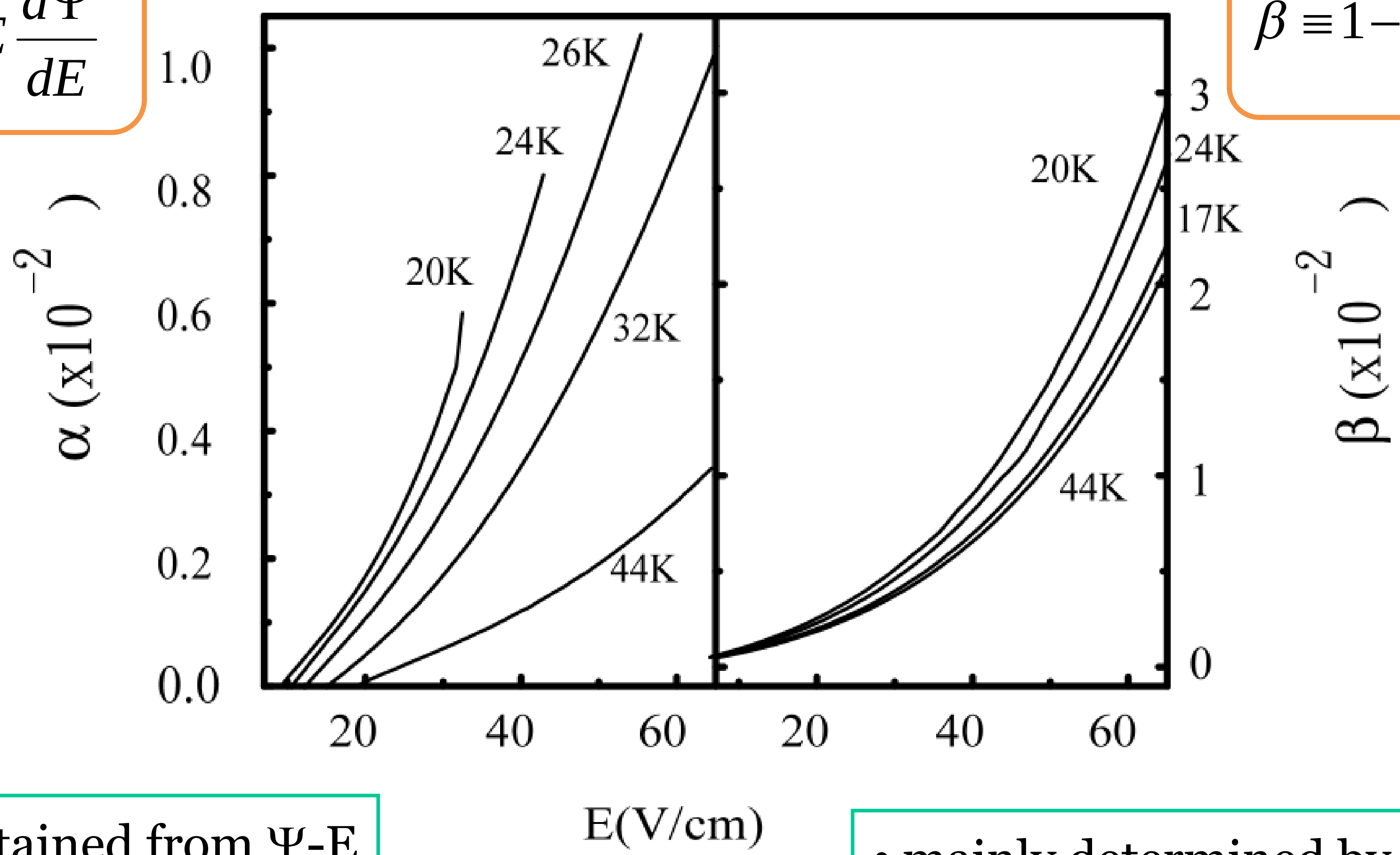
$\frac{\partial \Psi}{\partial E}$ increases abruptly

The J-E relation is almost linear and the same over different T's

α & β as Function of E

$$\alpha \equiv E\frac{d\Psi}{dE}$$

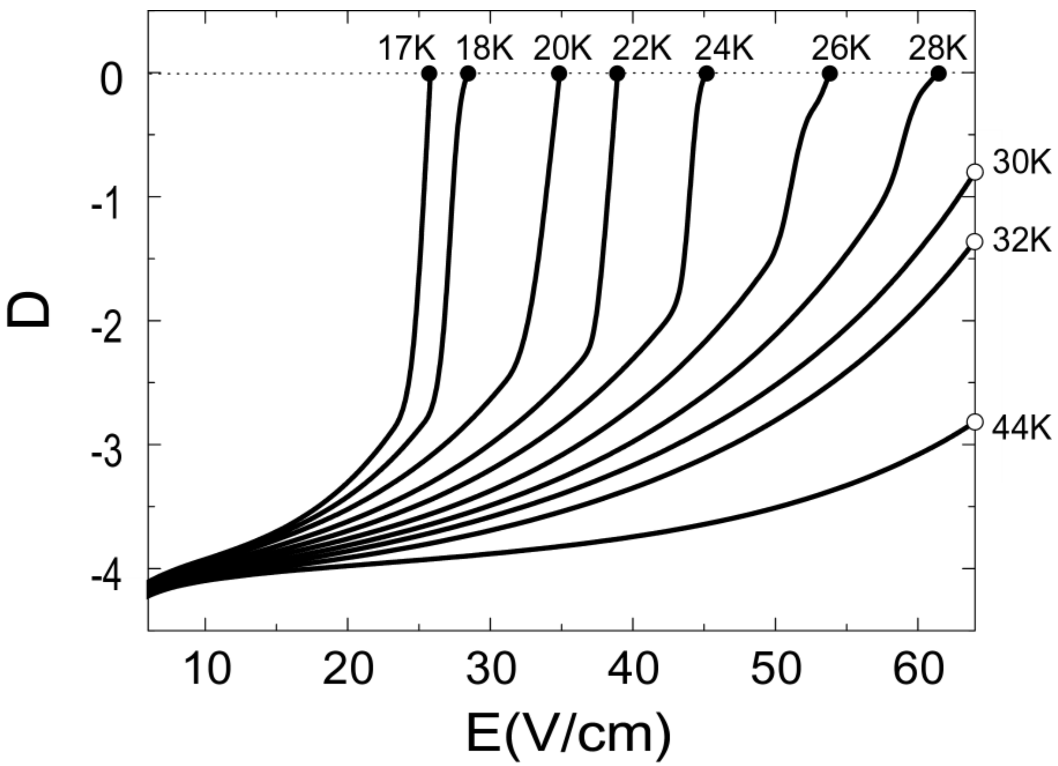
$$\beta \equiv 1-\frac{E}{J}\frac{dJ}{dE}$$



- obtained from Ψ-E
- As E ↑, α ↑
- As T_L ↑, α ↓

- mainly determined by ΔV_{xy}
- As E ↑, β ↑
- As T_L ↑, β ↑↓ not clear

D as Function of *E*



$$D = \beta^2 \tan^2 \Psi + 2\alpha(2-\beta)\tan\Psi + \alpha^2 - 4(1-\beta) > 0$$

0.3 2.4 10^{-4} -4 10^{-2}

"D" increases and changes its sign from negative to positive for 16K ~28K

- $\beta \cong 10^{-2} \Rightarrow$

  $\beta^2 tan^2\Psi \cong 0.3$
- $\alpha \cong 10^{-2} \Rightarrow$

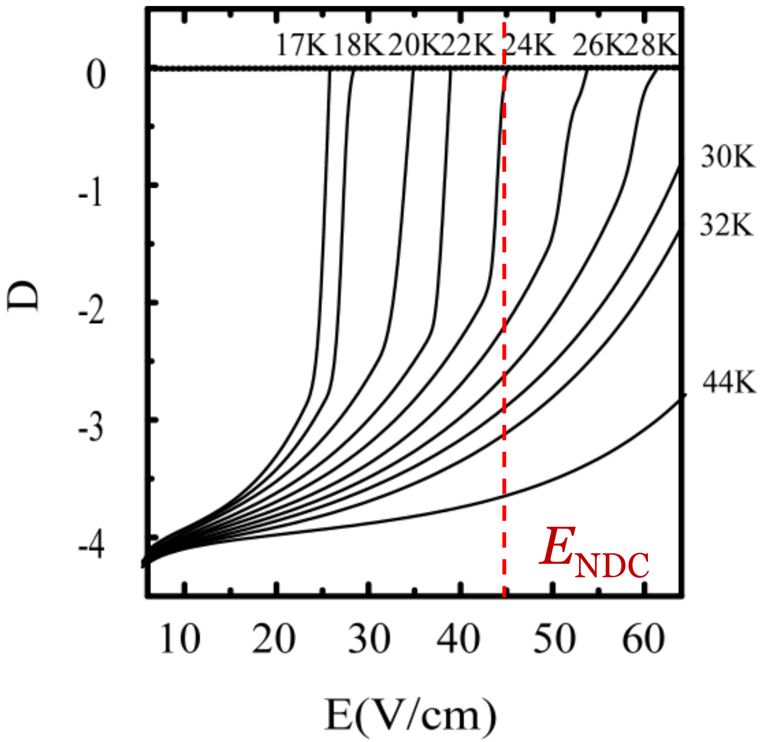
  $\alpha^2 \cong 10^{-4}$
- $2\alpha(2-\beta)\tan\Psi \cong 2.4$

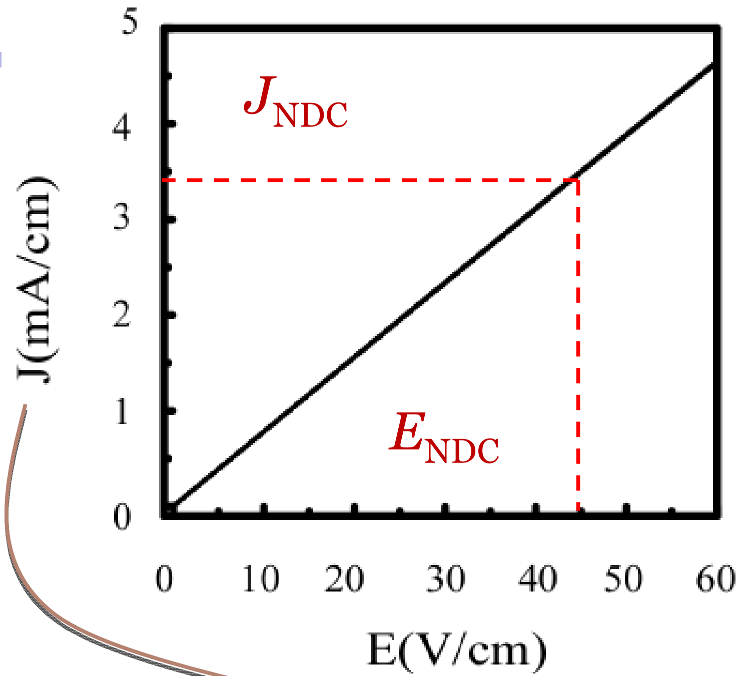
  $4(1-\beta) \cong 4$

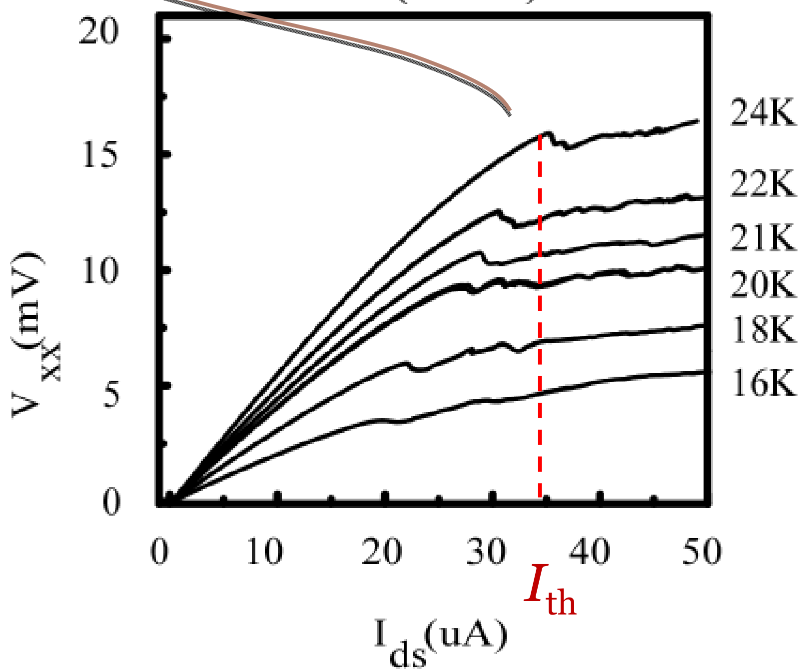
so $2\alpha(2-\beta)\tan\Psi - 4$ dominate the D value

α dominates the D behavior

I_{NDC} = I_{th}







$$D = \beta^2 \tan^2 \Psi + \boxed{2\alpha(2-\beta)\tan\Psi} + \alpha^2 \boxed{-4(1-\beta)}$$

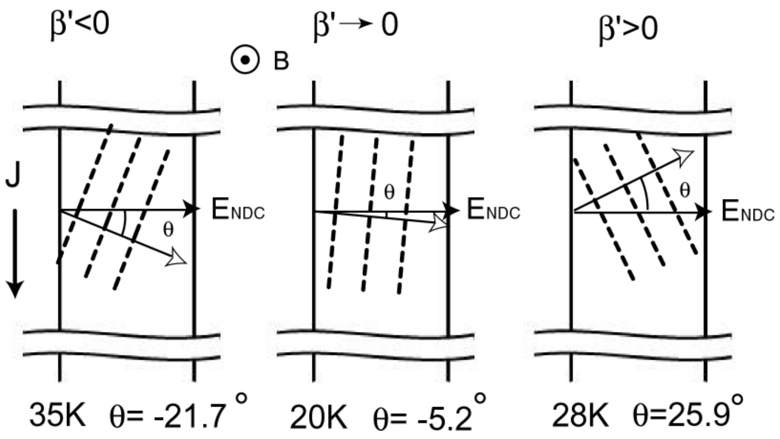
T_L	(K)	24
E_{NDC}	V/cm	45.0
I_{NDC}	μA	34.9
I_{th}	μA	35.0

Domain growth of space charge in NDC

the angle *between E* and the eigenvector

$$\theta = \frac{\Psi + \phi}{2} - \frac{\pi}{4}$$

$$\phi \equiv \tan^{-1}\left(\frac{\beta'}{\alpha'}\right)$$



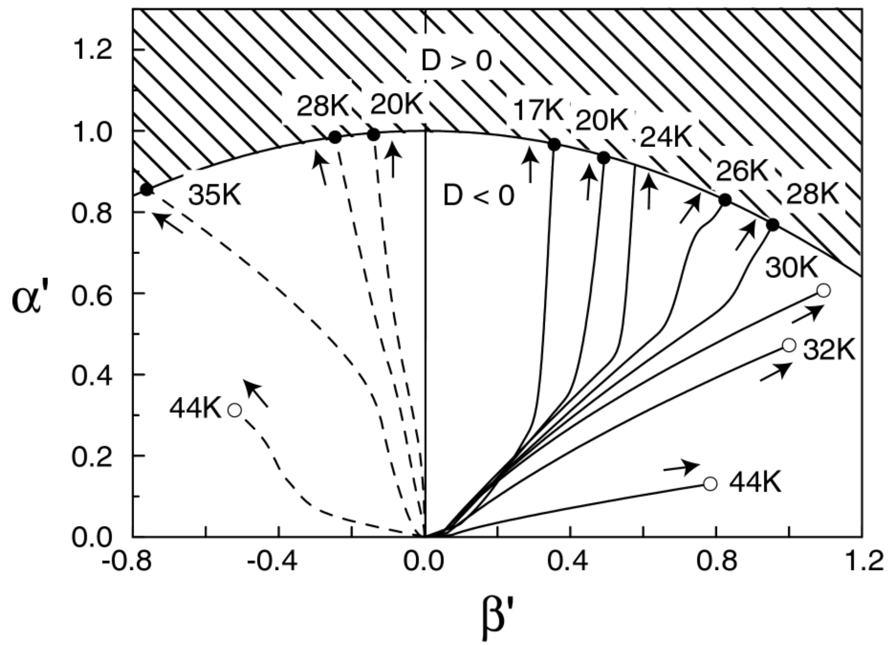
Sample 2 **Sample 2** **Sample1**

β dominates the growth direction

$\alpha' = \alpha \tan\Psi \qquad \beta' = \beta \tan\Psi$

$$D = \beta^2 \tan^2\Psi + 2\alpha(1+\beta)\tan\Psi + \alpha^2 - 4\beta > 0$$

$$1 - \alpha' - \frac{\beta'^2}{4} < 0$$



Dependence of α 'and β' on E. *The arrow marks* the direction of increasing E. Along the parabola the electric field reaches E_{NDC}.

Physical Origin of Instability

- Trend of Instability
  - ρ_{xx} decreases & $\Psi \to \pi/2$ as E$\uparrow$
    - Electric field gives the opposite effect to electron heating
    - i.e. Scattering rates decreases with increasing *E*
- T_L > 16K
  - Acoustic phonon scattering $\to \rho_{xx}$

Nonlinear transport in 2DEG:

- Two mechanisms

(a) Effects of E-filed on the distribution function $f_T(\varepsilon)$
(b) Effects of E-filed on the kinematics of electron scattering

- As $\tau_{in} >> \tau_q$, effect (a) dominates.

τ_{in}: inelastic scattering time
τ_q : quantum or single particle relaxation time
$f_T(\varepsilon)$: at E=o, Fermi-distribution

DC E-field changes f(ε): a theoretical approach

PHYSICAL REVIEW B **71**, 115316 (2005)

Theory of microwave-induced oscillations in the magnetoconductivity of a two-dimensional electron gas

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(Received 10 February 2004; revised manuscript received 22 September 2004; published 21 March 2005)

$$\sigma_{dc}^{D} = \frac{e^2 \nu_0 v_F^2}{2\omega_c^2 \tau_{tr}}$$

$$\tau_{\mathrm{tr,B}} = \tau_{tr}\frac{\nu_0}{\nu(\varepsilon)}$$

Kinetic equation

$$\mathrm{St}_{\omega}\{f\} + \mathrm{St}_{\mathrm{dc}}\{f\} = -\,\mathrm{St}_{\mathrm{in}}\{f\}$$

Kubo formula

Self-consistent Born approximation

Ref: A. Dmitriev,etc. *Phys. Rev. Lett.* **91** p226802 (2003)

$$\mathrm{St}_{\omega}\{f\} = \frac{\mathcal{E}_{\omega}^2}{4\omega^2}\sum_{\pm}\frac{e^2 v_F^2 \tau_{\mathrm{tr},B}^{-1}(\varepsilon+\omega)[f(\varepsilon+\omega)-f(\varepsilon)]}{2(\omega\pm\omega_c)^2 + \tau_{\mathrm{tr},B}^{-2}(\varepsilon+\omega) + \tau_{\mathrm{tr},B}^{-2}(\varepsilon)} + \{\omega \to -\omega\}.$$

As ω→0, St $_{\omega}$\{f\}= St $_{\mathrm{dc}}$\{f\}

$$\mathrm{St}_{\mathrm{dc}}\{f\} = \nu^{-1}(\varepsilon)\partial_{\varepsilon}[\nu(\varepsilon)e^2\mathcal{E}_{\mathrm{dc}}^2 D_B(\varepsilon)\partial_{\varepsilon}f(\varepsilon)]$$
$$= \varepsilon_{\mathrm{dc}}^2\frac{\sigma_{\mathrm{dc}}^{D}}{\nu_0\tilde{\nu}(\varepsilon)}\partial_{\varepsilon}[\tilde{\nu}^2(\varepsilon)\partial_{\varepsilon}f(\varepsilon)].$$

$$\mathcal{E}_{\omega}^2\frac{\sigma_{\omega}^{D}}{2\omega^2\nu_0}\sum_{\pm}\tilde{\nu}(\varepsilon\pm\omega)[f(\varepsilon\pm\omega)-f(\varepsilon)]$$
$$+\,\mathcal{E}_{\mathrm{dc}}^2\frac{\sigma_{\mathrm{dc}}^{D}}{\nu_0\tilde{\nu}(\varepsilon)}\partial_{\varepsilon}[\tilde{\nu}^2(\varepsilon)\partial_{\varepsilon}f(\varepsilon)] = \frac{f(\varepsilon)-f_T(\varepsilon)}{\tau_{\mathrm{in}}}$$

Key formula, but we only need DC term

DC E-field changes f(ε): a theoretical approach

$$\boxed{\sigma_{xx} = \int d\varepsilon \sigma_{dc}(\varepsilon)[-\partial_\varepsilon f(\varepsilon)]}$$

Transport relaxation time: $\tau_{tr,B}(\varepsilon) = \tau_{tr} \dfrac{N_0}{N(\varepsilon)}$

$$\sigma_{dc}(\varepsilon) = \frac{e^2 N(\varepsilon) v_F^2}{2} \frac{\tau_{tr,B}^{-1}(\varepsilon)}{\omega_c^2 + \tau_{tr,B}^{-2}(\varepsilon)}$$

DOS $N(\varepsilon)$, $\tilde{N}(\varepsilon) = \dfrac{N(\varepsilon)}{N_0}$

DOS (2DEG): $N_0 = \dfrac{m}{\pi \hbar^2}$

dc Drude conductivity per spin in strong B

$$\sigma_{dc}^D = \frac{e^2 N_0 v_F^2}{2\omega_c^2 \tau_{tr}} \qquad \omega_c \tau_{tr} \gg 1$$

$$\Rightarrow \sigma_{dc}(\varepsilon) = \sigma_{dc}^D \tilde{N}^2(\varepsilon)$$

Notice : notation change
DOS ν(ε) →N(ε)

Stationary kitnetic equation

$$\varepsilon_{dc}^2 \frac{\sigma_{dc}^D}{N_0 \tilde{N}(\varepsilon)} \frac{\partial}{\partial \varepsilon}\left[\tilde{N}^2(\varepsilon) \frac{\partial}{\partial \varepsilon} f(\varepsilon)\right] = \frac{f(\varepsilon) - f_T(\varepsilon)}{\tau_{in}}$$

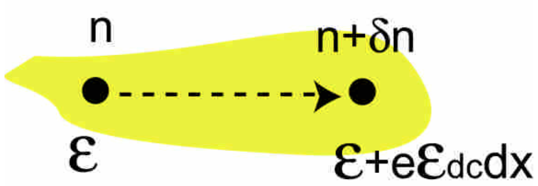
Ref. A. Dmitriev,etc. *Phys. Rev. B.* **71** p115316 (2005)

A simple derivation for $E_{dc} \rightarrow \delta f(\varepsilon)$

Continuous equation:

$$\frac{\partial n}{\partial t} = -\frac{\partial J}{\partial x} \qquad (1)$$

$$\varepsilon \rightarrow \varepsilon + d\varepsilon = \varepsilon + e\varepsilon_{dc} dx$$



$$n \rightarrow n + \delta n$$
$$J \rightarrow J + \delta J$$
$$f \rightarrow f_T + \delta f$$
$$N(\varepsilon) \approx N_0 + \delta N$$

Diffusion coeff at B

$$D_B = \frac{v_F^2}{2}\omega_c^2 \tau_{tr,B}$$

$$\delta n = N(\varepsilon) f(\varepsilon) d\varepsilon$$

$$\frac{\partial \delta n}{\partial t} = N(\varepsilon) d\varepsilon \frac{\partial}{\partial t} f(\varepsilon) = N(\varepsilon) d\varepsilon \frac{f - f_T}{\tau_{in}} \qquad (2)$$

$$J = -D_B \nabla n$$

$$\delta J = -D_B \nabla \delta n = -D_B \nabla (N(\varepsilon) f(\varepsilon)) d\varepsilon$$

$$\frac{\partial \delta J}{\partial x} \ldots$$

$$= \ldots \left[D_B N(\varepsilon) \frac{\partial f}{\partial \varepsilon} \nabla \varepsilon \right] d\varepsilon$$

$$\Rightarrow \frac{\partial \delta J}{\partial x} = \partial_\varepsilon \left[N(\varepsilon) D_B (e\varepsilon_{dc})^2 \partial_\varepsilon f \right] d\varepsilon \qquad (3)$$

eq(2)=eq(3)

$$\Rightarrow \quad \frac{f - f_T}{\tau_{in}} = N(\varepsilon)^{-1} \partial_\varepsilon \left[N(\varepsilon) D_B (e\varepsilon_{dc})^2 \partial_\varepsilon f \right]$$

eE dx after the diffusion at distance dx

⇒translates into the diffusion in energy,

ε + e E dx

DC E-field changes f(ε): a theoretical approach

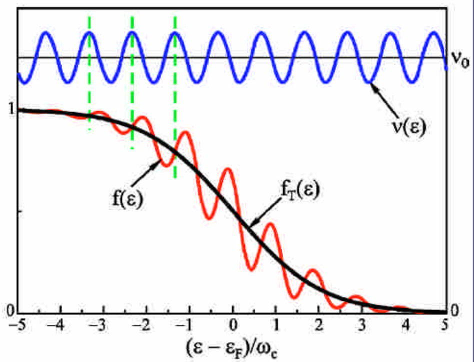
Stationary kitnetic equation

$$\varepsilon_{dc}^2 \frac{\sigma_{dc}^D}{N_0 \tilde{N}(\varepsilon)} \frac{\partial}{\partial \varepsilon}\left[\tilde{N}^2(\varepsilon)\frac{\partial}{\partial \varepsilon} f(\varepsilon)\right] = \frac{f(\varepsilon) - f_T(\varepsilon)}{\tau_{in}}$$

Overlapping LL

$$\tilde{N} = 1 - 2\delta\cos\frac{2\pi\varepsilon}{\omega_c}$$

$$\delta = \exp\left(-\frac{\pi}{\omega_c \tau_q}\right) << 1$$



$$\frac{\sigma_{\mathrm{ph}}}{\sigma_{\mathrm{dc}}^D} = 1 + 2\delta^2\left[1 - \frac{\mathcal{P}_\omega \frac{2\pi\omega}{\omega_c}\sin\frac{2\pi\omega}{\omega_c} + 4\mathcal{Q}_{\mathrm{dc}}}{1 + \mathcal{P}_\omega \sin^2\frac{\pi\omega}{\omega_c} + \mathcal{Q}_{\mathrm{dc}}}\right]$$

As ω=0

$$\Rightarrow \frac{\sigma_{xx}}{\sigma_{dc}^D} = 1 + 2\delta^2\left(\frac{1 - 3Q_{dc}}{1 + Q_{dc}}\right)$$

$$T >> \omega$$

$$\tau_{in} \sim \frac{1}{T^2}$$

$$Q_{dc} = \frac{2\tau_{in}}{\tau_{tr}}\left(\frac{eE_{dc}v_F}{\omega_c^2}\right)^2\left(\frac{\pi}{\hbar\omega_c}\right)^2$$

$$\rho_{xx} \sim \rho_{xy}^2 \sigma_{xx}$$

$$\Rightarrow \frac{\rho_{xx}}{\rho_{xx}(E_{dc}=0)} = \frac{1 + 2\delta^2\left(\frac{1 - 3Q_{dc}}{1 + Q_{dc}}\right)}{1 + 2\delta^2}$$

Data analysis strategy

(1) Determine $\tau_{\mathrm{tr,B}}$

$$\tau_{tr,B} = \frac{e^2 N_0 v_F^2}{2\omega_c^2 \sigma_{dc}^D}$$

$\sigma_{dc}^D \to \rho_{xx}(\mathrm{E} \to 0)$ from $\mathrm{V_{xx}}$-I

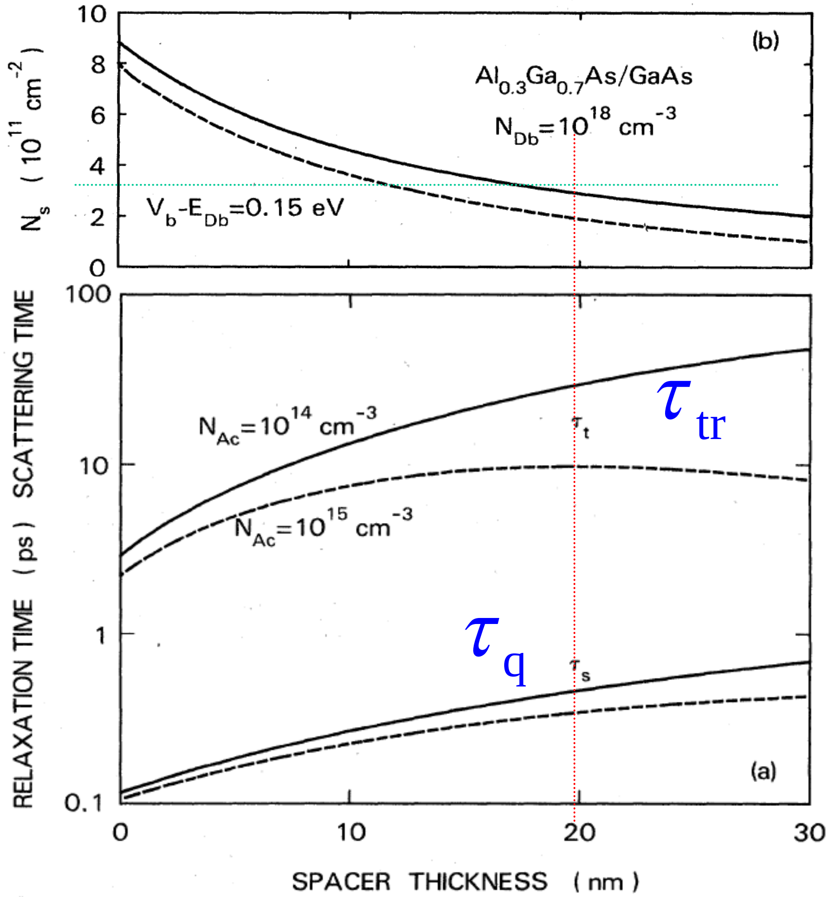
(2) Determine τ_{q}

(3) Fit $\rho_{xx}(\mathrm{E_{dc}})/\rho_{xx}(\mathrm{E_{dc}}=0)$

fitting parameter τ_{in}

(4) Check $\tau_{\mathrm{in}}(\mathrm{T})$ relation

Determine τ_q



$$\frac{1}{\tau}=\frac{2\pi mN_i}{\hbar^3}\int\frac{d^3k'}{(2\pi)^3}f(\theta)\left|u\left(2k_F\sin\left(\frac{\theta}{2}\right)\right)\right|^2\frac{\delta(k'-k_F)}{k'}$$

remote impurity: addation factor $\exp(-4k_F d_s \sin(\theta/2))$

d_s : spacer thickness

Single-particle relaxation time versus scattering time in an impure electron gas

Ref. S. Das Sarma, Frank Stern. *Phys. Rev. B.* **32** p8442 (1985)

4.2K / B=0T

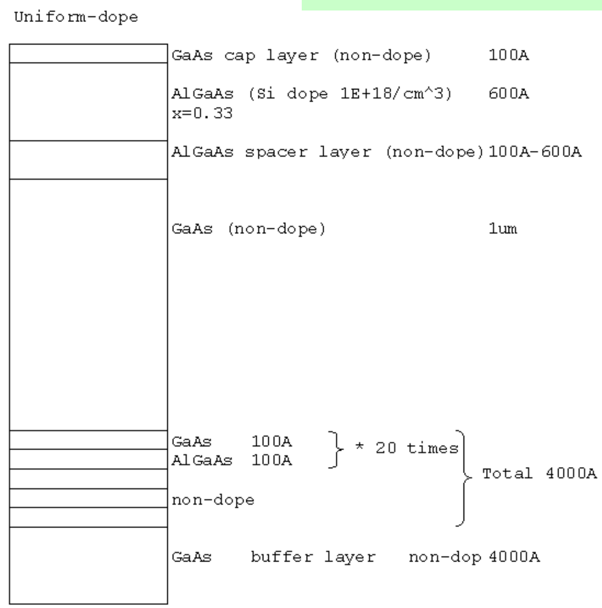
τ_{tr}=32ps

τ_q~1.6ps (from SdH osc.)

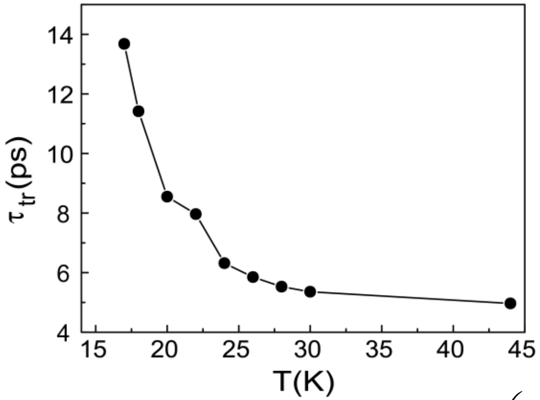
Assume

$$\frac{\tau_{tr}}{\tau_q}\sim 20$$

Our wafer structure

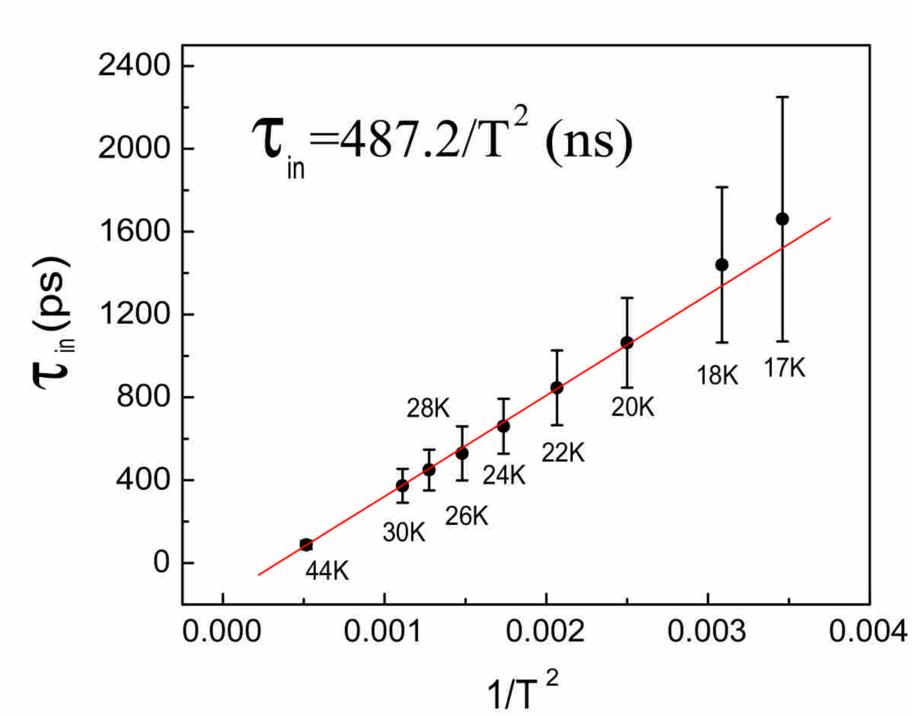


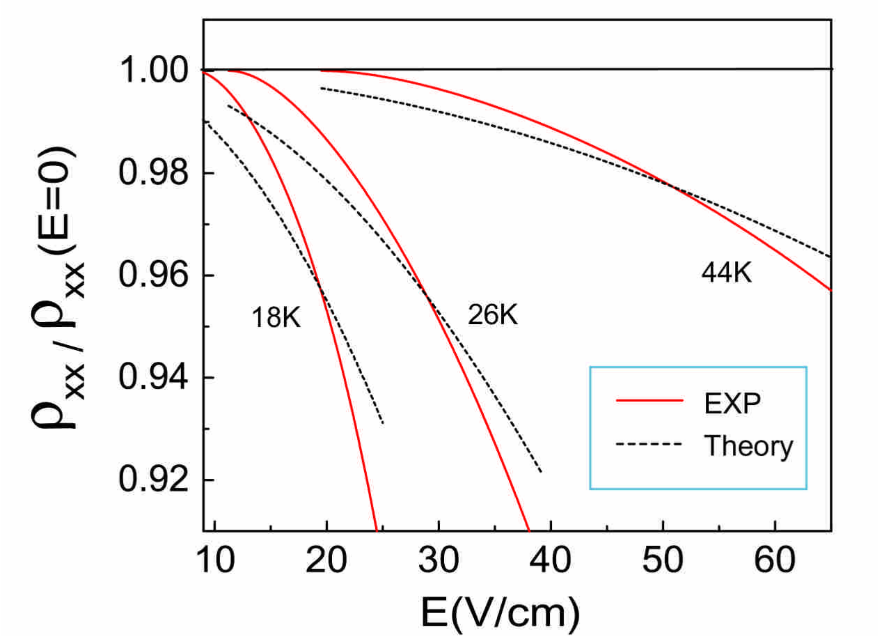
Analysis results



$$\tau_{tr} = \frac{e^2 N_0 v_F^2}{2\omega_c^2 \sigma_{dc}^D}$$

$$\Rightarrow \frac{\rho_{xx}}{\rho_{xx}(E_{dc}=0)} = \frac{1+2\delta^2\left(\frac{1-3Q_{dc}}{1+Q_{dc}}\right)}{1+2\delta^2}$$





$B < 1T$

- $\text{exp}: \tau_{in} = \frac{10 \sim 12}{T^2} ns$

theory: $\tau_{in} = \frac{5 \sim 4}{T^2} ns$

Ref. *Phys. Rev. B.* **75** p081305 (2007)

Conclusion

- We have studied the current instability observed at *ν=2 Hall plateau in a 2DEG system at high* lattice temperatures, $T_L \sim 17\text{-}35K$
- We demonstrate that the instability is caused by the NDC predicted by Kurosawa et al.
- The nonlinearity of the longitudinal voltages is the dominant effect to drive the system into NDC
- The nonlinearity of the Hall voltages govern the domain growth progress
- Physical origin of the nonlinearities inducing the NDC may be explained with electric field dependence of the scattering rate.