BROWN

PHYS 2010 Techniques in Experimental Physics

# Quantum Oscillations – Electronic Properties of a Two-Dimensional Electron Gas(2DEG)


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# INTRODUCTION (key parts)

## 1. MOSFET (Metal Oxide Semiconductor Field Effect Transistor)

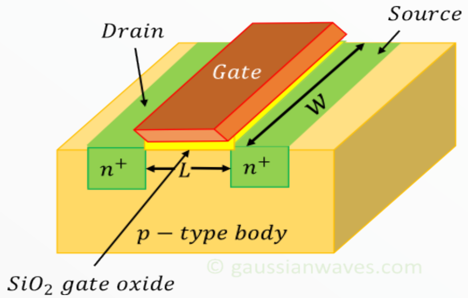



Fig.1: Typical n-MOSFET geometry

## 2. Formation of a 2DEG

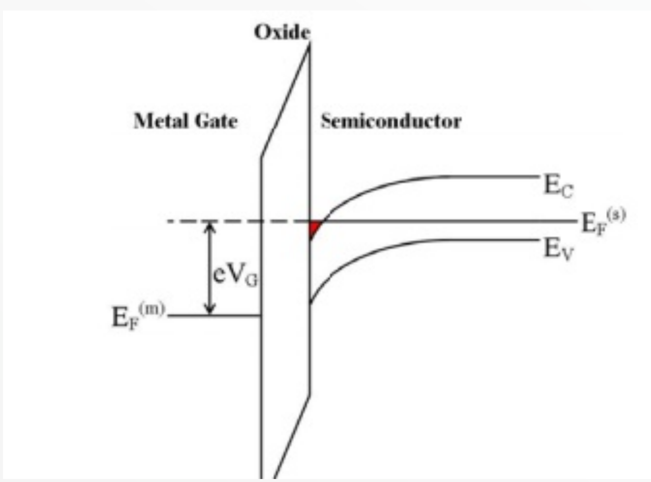



Fig.2: Band diagram of a MOSFET

## 3. 2DEG energy quantized to Landau levels at a magnetic field

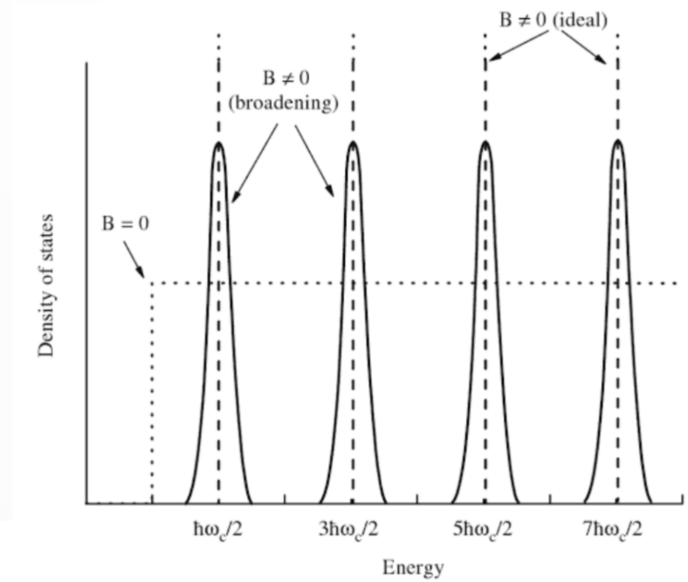
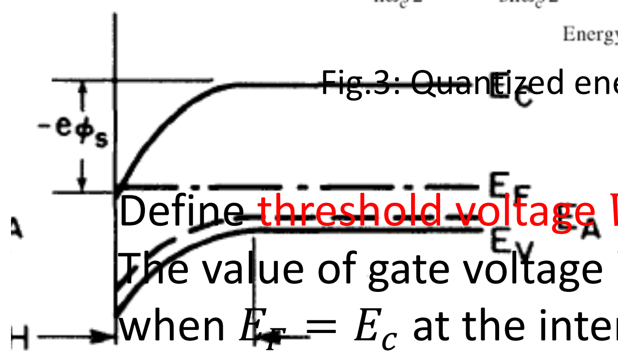



Fig.3: Quantized energy levels




Define threshold voltage $V_T$:
The value of gate voltage $V_G$ when $E_F = E_c$ at the interface of oxide and semiconductor

# INTRODUCTION (transport properties)

## Definitions:

Single layer **conductivity**:

$$\sigma = G\frac{L}{W} \quad (1)$$

Electron **density** per unit area:

$$N = Q/(e * A_{2DEG}) \quad (2)$$

Electron **mobility**:

$$\mu = v_d/E \quad (3)$$

**Mean free time**:

$$\tau = m^*\mu/e \quad (4)$$

## Useful equations:

Ohm's law:

$$\sigma = J/E \quad (5)$$

Single layer current density:

$$J = eNv_d \quad (6)$$

Assuming MOSFET as parallel plate capacitor:

$$C = \frac{\epsilon_{ox}}{t_{ox}} * A_{2DEG} \quad (7)$$

Capacitor equation:

$$Q = C * (V_G - V_T) \quad (8)$$

| | |
|---|---|
| Conductance | $G$ |
| Gate length | $L$ |
| Gate width | $W$ |
| 2DEG area | $A_{2DEG}$ |
| Drift velocity | $v_d$ |
| Electric field | $E$ |
| 2DEG Effective mass | $m^*$ |
| Dielectric constant | $\epsilon_{ox}$ |
| Oxide thickness | $t_{ox}$ |

## Key equations:

$$\sigma = G\frac{L}{W} \quad (1)$$

$$N = \frac{\epsilon_{ox}}{et_{ox}}(V_G - V_T) \quad (9)$$

$$\mu = \frac{\sigma}{eN} \quad (10)$$

$$\tau = m^*\mu/e \quad (4)$$

**Measure**

**Calculate**

# INTRODUCTION (Landau levels)

**Definitions:**

$$N = \int_E \quad g(E)f(E)dE \qquad (11)$$

$$N \approx m^*/\pi\hbar^2(E_F - E_c) \qquad (12)$$

Landau levels, Landau index $n = 0,1,2 \ldots$

$$E_F - E_c = \left(n + \frac{1}{2}\right)\hbar\omega_c \qquad (13)$$

Cyclotron frequency

$$\omega_c = \frac{eB}{m^*} \qquad (14)$$

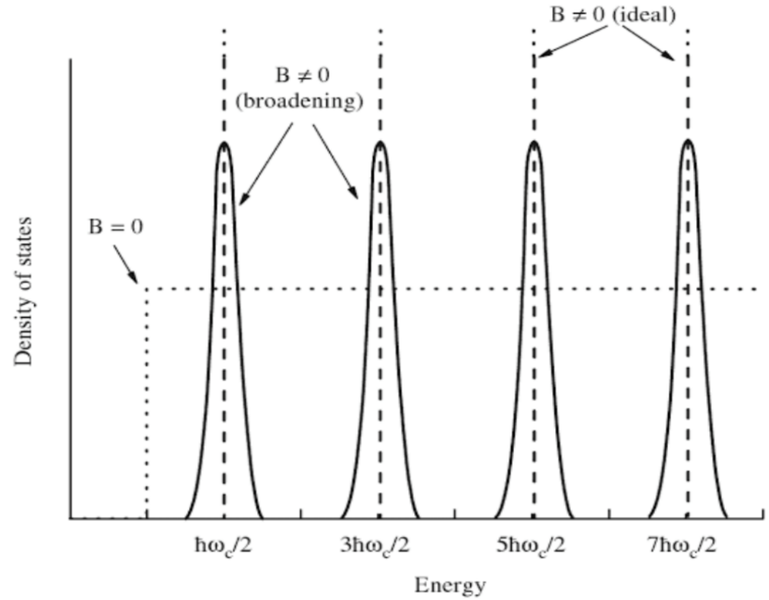


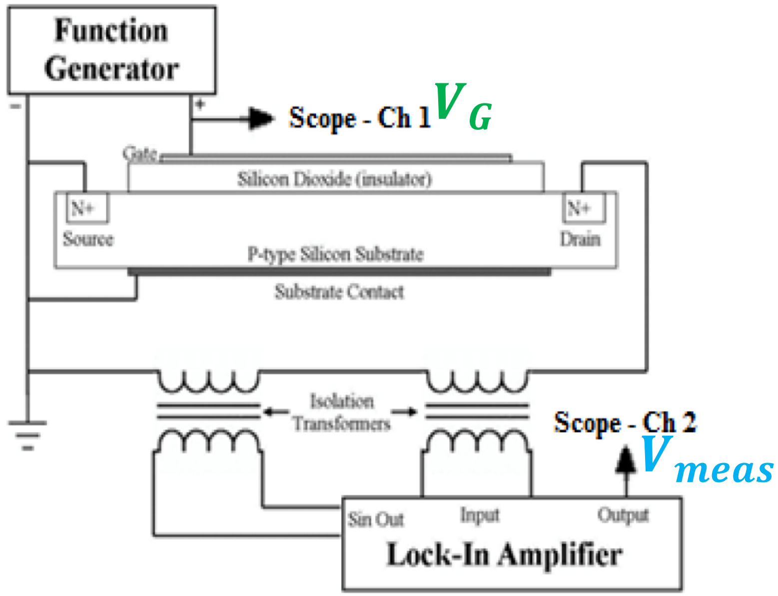

Fig.3: Quantized energy levels

**Key equation:**

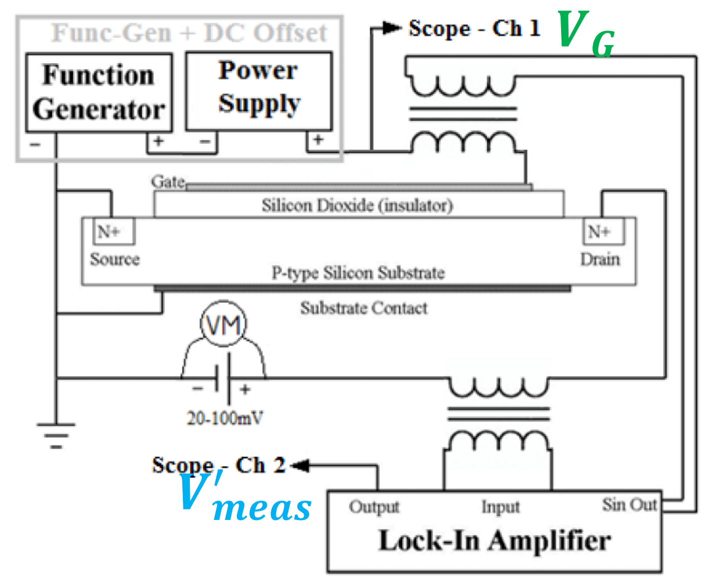
$$\boxed{V_G = V_T + \frac{e^2 B t_{ox}}{\pi\hbar\epsilon_{ox}}\left(n + \frac{1}{2}\right) \qquad (15)}$$

**Measure**
**Calculate**

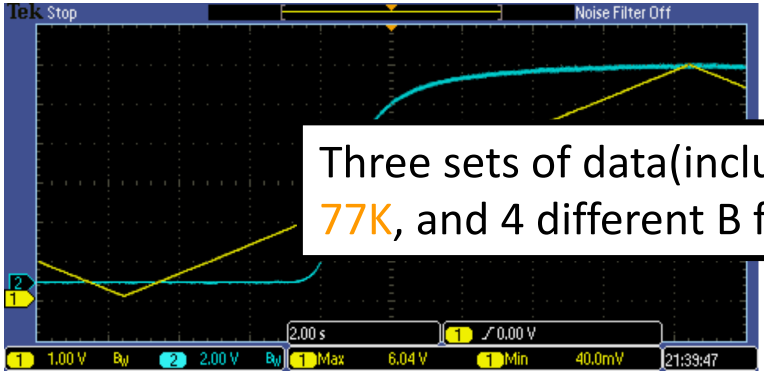
# EXPERIMENT

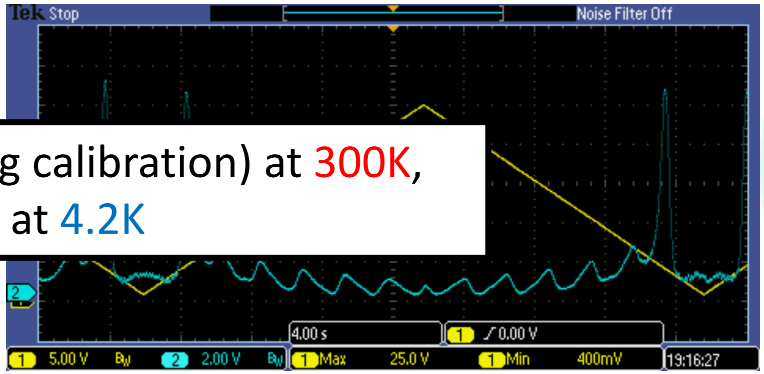



Conductance circuit




Transconductance circuit




Three sets of data(including calibration) at 300K, 77K, and 4 different B field at 4.2K

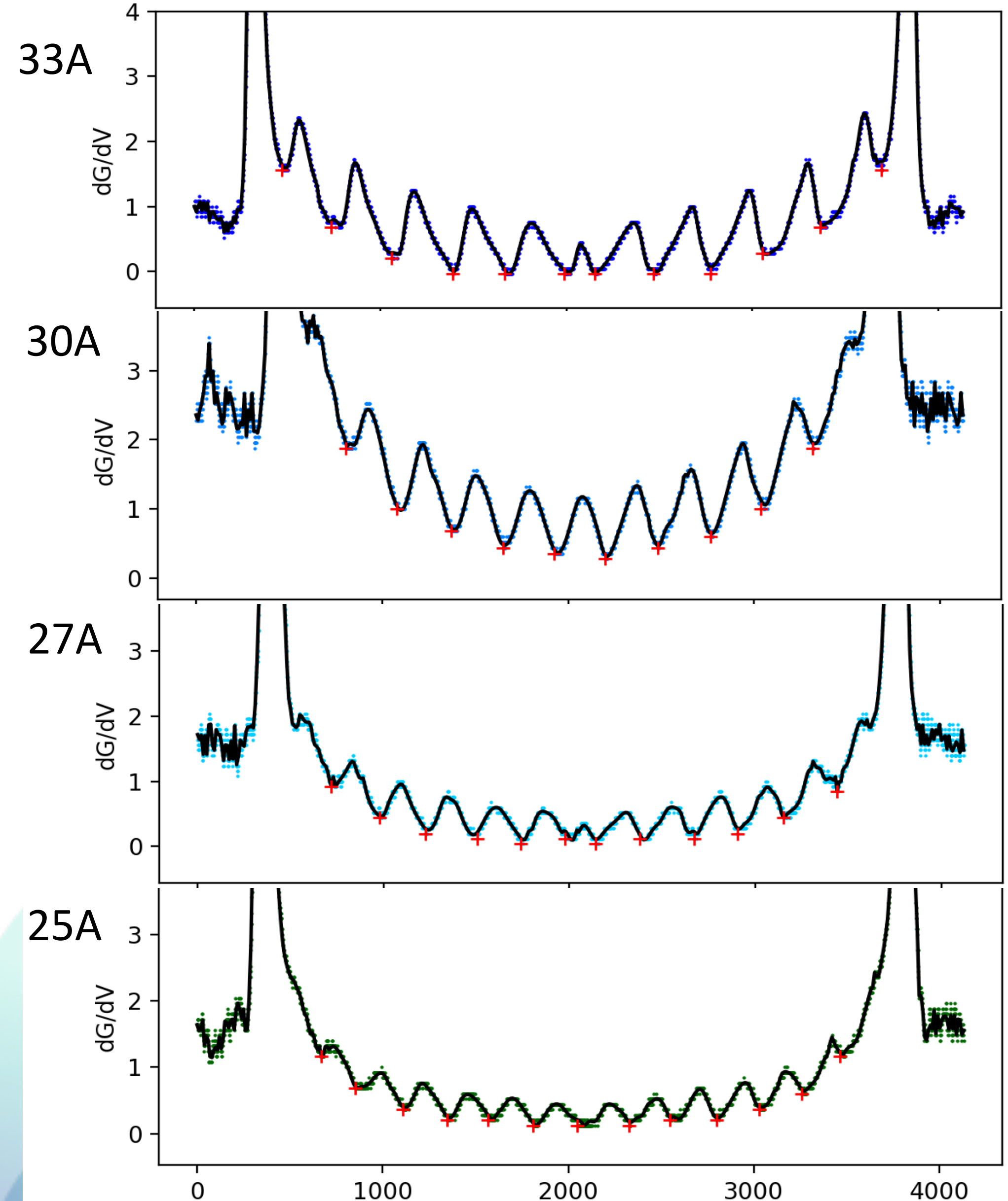
Calibration relates $G$ and $V_{meas}$

$G$ vs $V_G$

Lock-in setting:
freq: ~ 92.4Hz
phase: ~ 117 deg

$\frac{\partial G}{\partial V_G}$ vs $V_G$

# DATA ANALYSIS - A. Transconductance Data



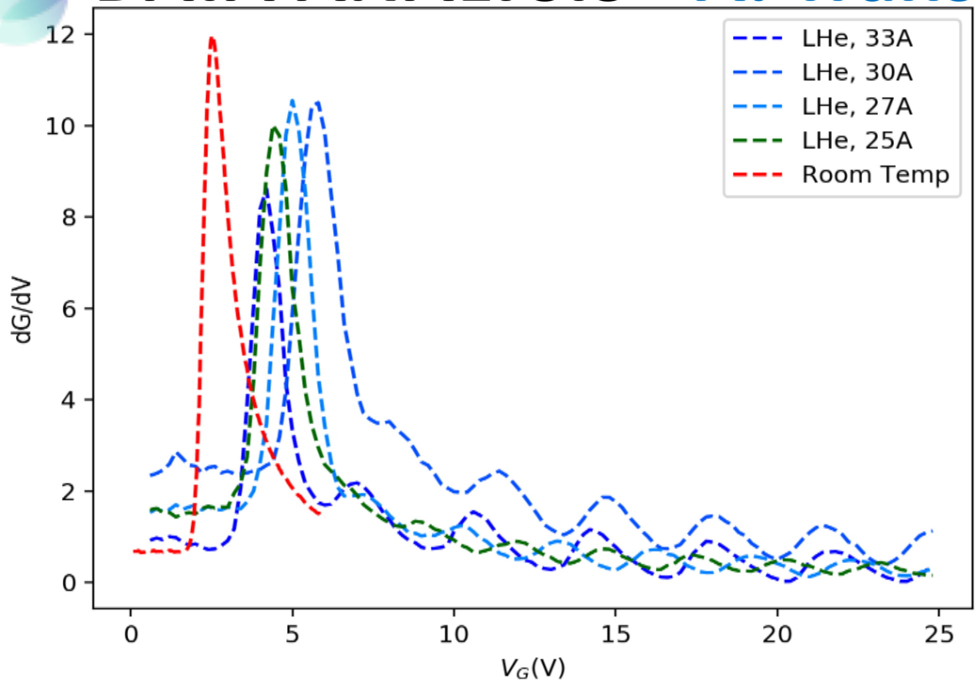

0. Preprocess data
1. Find gate voltage at local minimum
2. Determine Landau index
3. Fit to a straight line

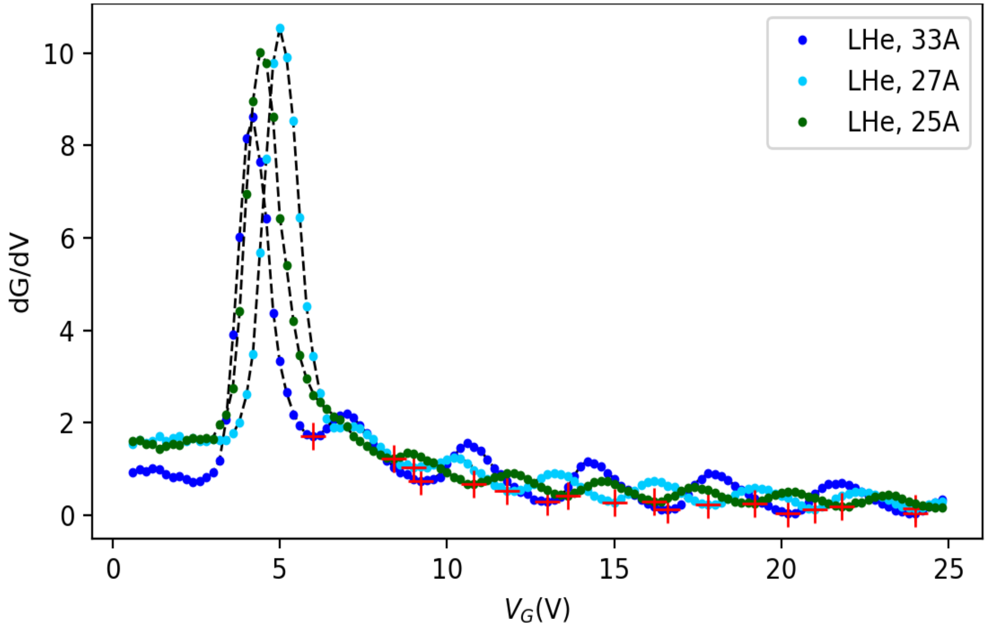
Using peak detect algorithm to find local minimum of a data set. A look-ahead parameter needs to be adjusted.

Then Average symmetric $V_G$.

“Post-averaging” method.

# DATA ANALYSIS - A. Transconductance Data




1. Preprocess data
2. Find gate voltage at local minimum
3. Determine Landau index
4. Fit to a straight line

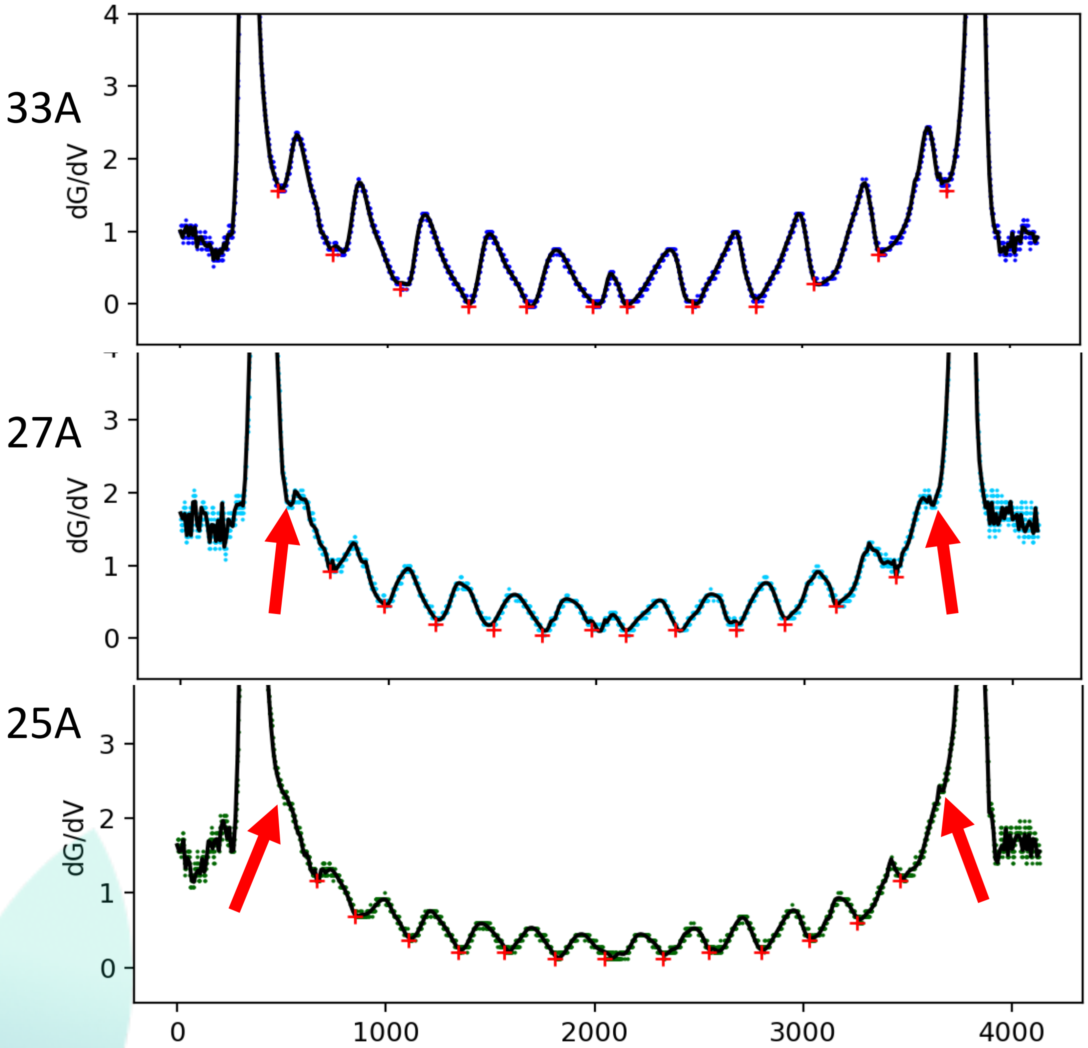
First average all $V_{meas}$ for same $V_G$.

Using peak detect algorithm to find local minimum of a data set. A look-ahead parameter needs to be adjusted.

"Pre-averaging" method.

# DATA ANALYSIS – A. Transconductance Data

1. Preprocess data
2. Find gate voltage at local minimum
3. Determine Landau index
4. Fit to a straight line



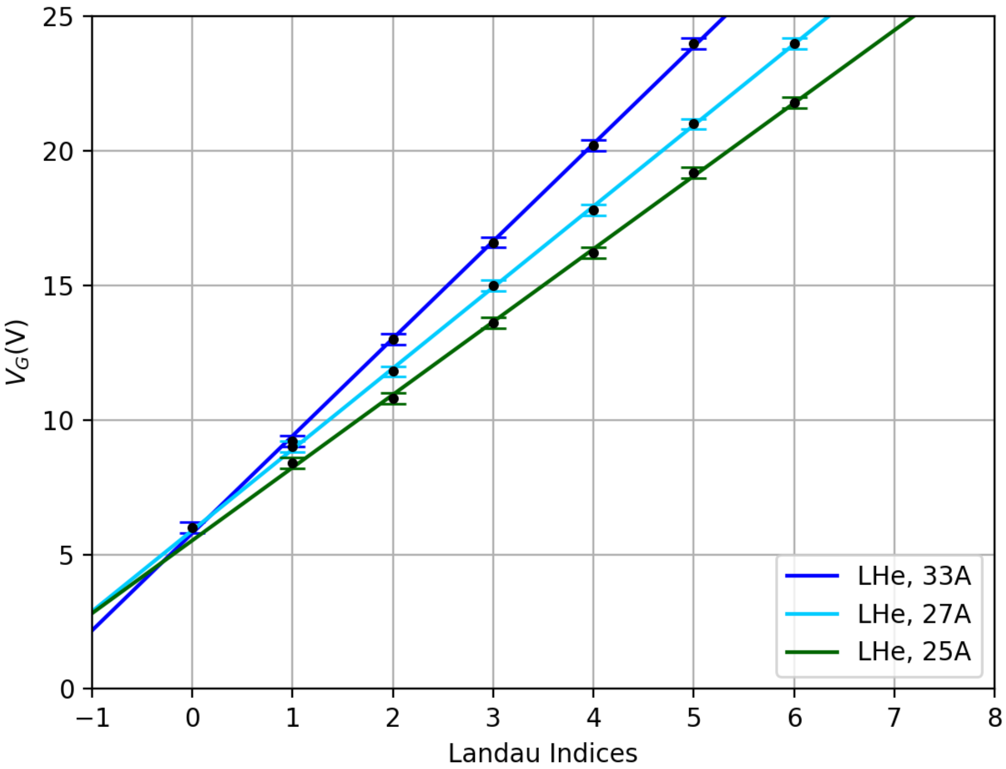

First Landau level is obscured by the signal. Start from 0, 1, 1 for 33A, 27A, 25A.

Theoretically,

$$V_G = V_T + \frac{e^2 B t_{ox}}{\pi \hbar \epsilon_{ox}} \left( n + \frac{1}{2} \right)$$

Check if they converge to one point when n= - ½.

# DATA ANALYSIS – A. Transconductance Data




1. Preprocess data
2. Find gate voltage at local minimum
3. Determine Landau index
4. Fit to a straight line

$$V_G = V_T + \frac{e^2 B t_{ox}}{\pi \hbar \epsilon_{ox}}\left(n + \frac{1}{2}\right)$$

They do converge to one point when n= - ½, this value is just $V_T$. Slope of the line gives $t_{ox}$. Error comes from the standard deviation of three values at different magnetic field and the peak detect process.

Post-averaging way: $V_T = 4.192 \pm 0.369\ V$

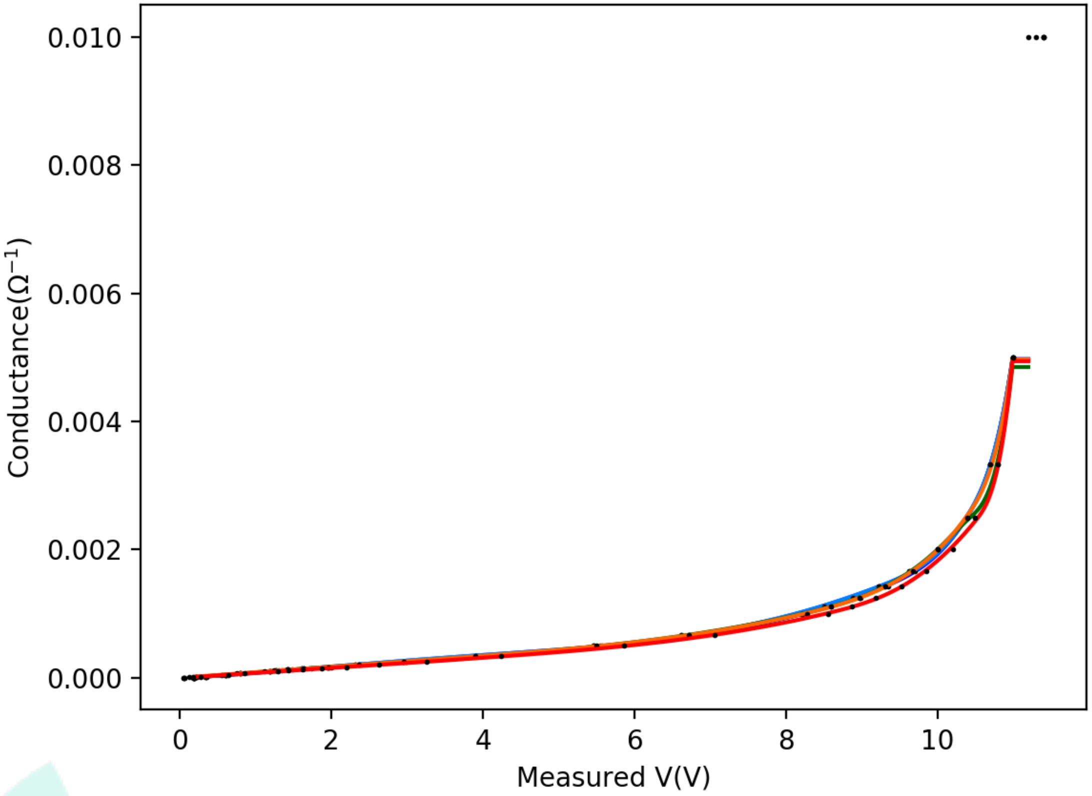
$t_{ox} = 281.274 \pm 3.170\ nm$

(At LHe temperature)

Pre-averaging way: $V_T = 4.178 \pm 0.383\ V$

$t_{ox} = 281.904 \pm 3.368\ nm$

# DATA ANALYSIS – B. Conductance Data

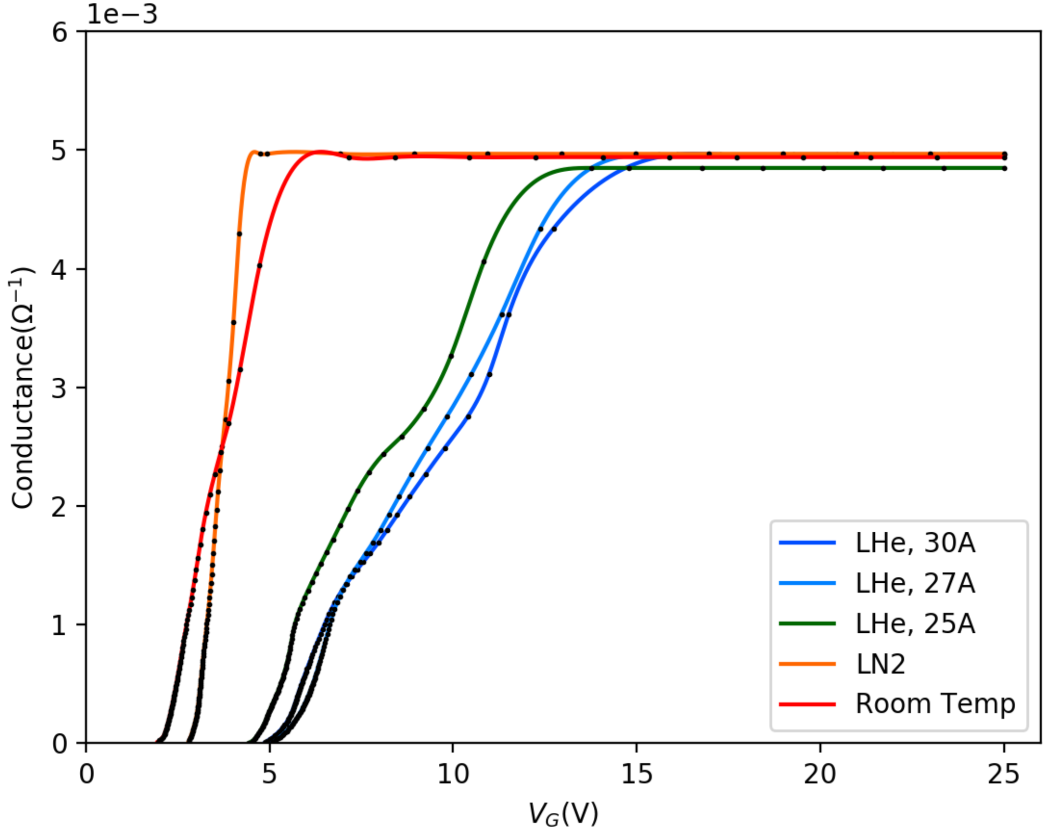



Calibration curve
($G\ vs\ V_{meas}$)

From data points to continuous curve:
Spline interpolation in [0, 11.2] $V_{meas}$ space

Calibration data does not make sense, so a cutoff measured voltage $V_{cutoff} = 11V$ is set.

# DATA ANALYSIS – B. Conductance Data



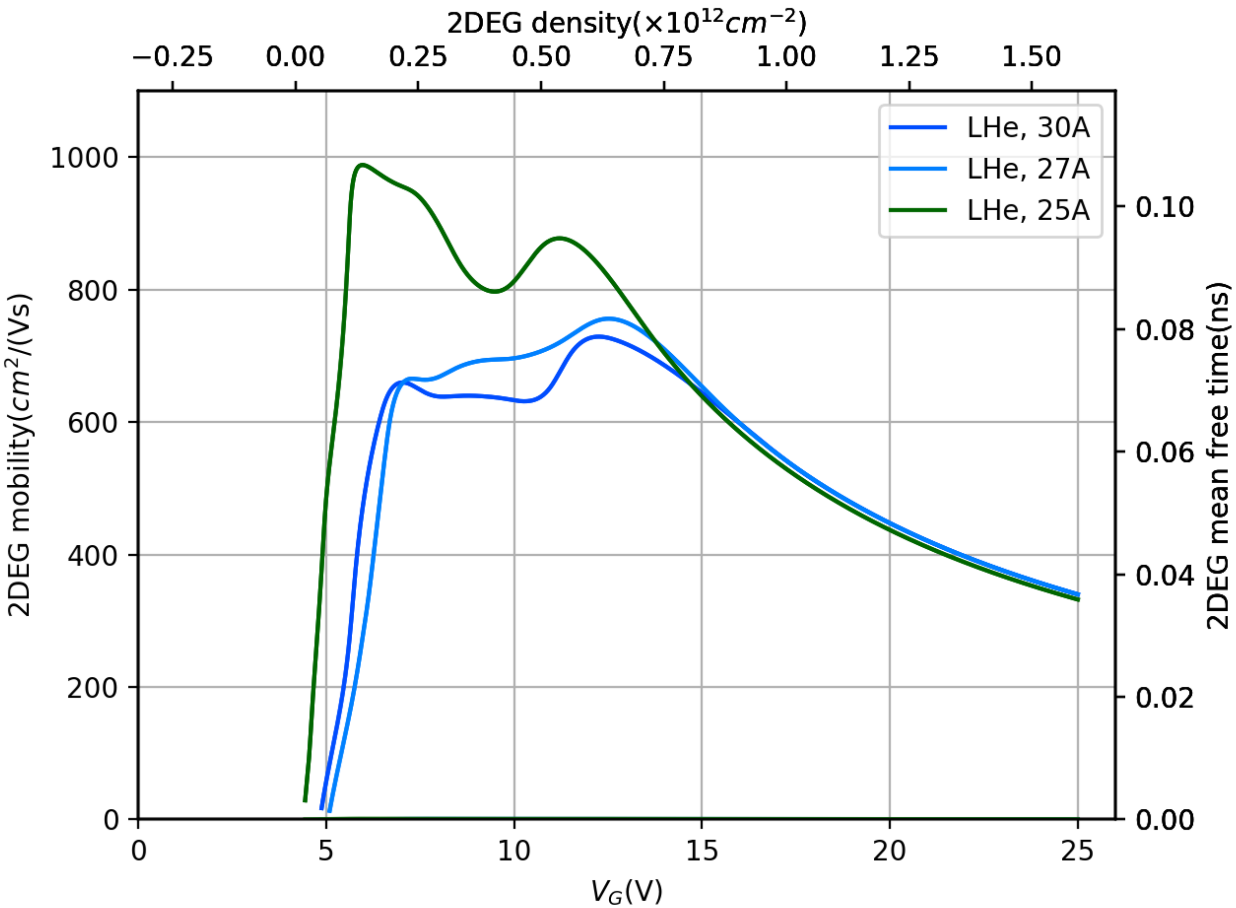

Calibration curve ($G\ vs\ V_{meas}$)

Original scope data

Averaged scope data ($V_G\ vs\ V_{meas}$)

Conductance curve ($G\ vs\ V_G$)

# DATA ANALYSIS – C. Electronic properties




Conductivity **increases with gate voltage** until the 2DEG is **saturated**, at that time all available electrons are in conduction band.

Electron mobility and mean free time **peaks at nearly threshold voltage** and **drops** with increasing gate voltage.

$V_T = 4.73V$ at 4.2K
$V_T = 2.76V$ at 77K
$V_T = 1.92V$ at 300K

Alternative $V_T$ definition shows that $V_T$ has a temperature dependence - **$V_T$ decreases with increasing temperature.**

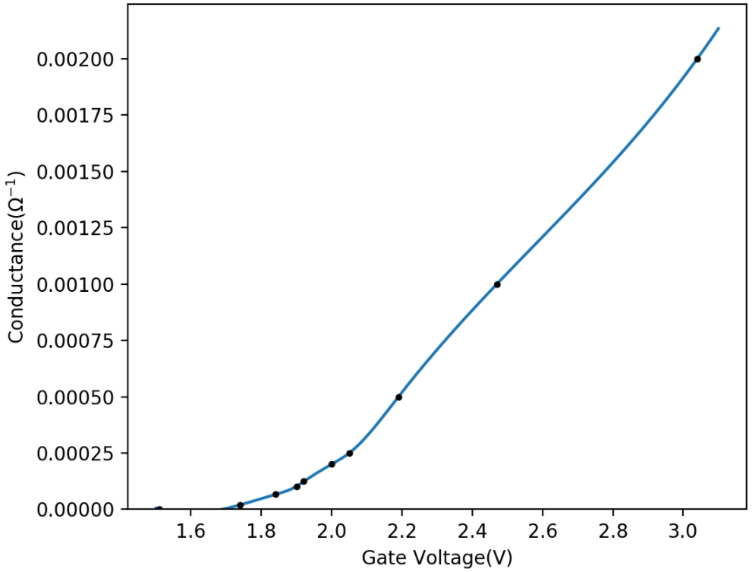
# DISCUSSION AND ADVICE

2 ways to take data:

1. Feed in low-frequency triangle wave to Gate as instructed in the manual
    - Can not get optimized signal at every gate voltage
    - Collect data easily – save waveform directly from scope

OK to get correct $G - V_G$ curve as long as:
Keep lock-in settings exactly same & calibration data has single value correspondence

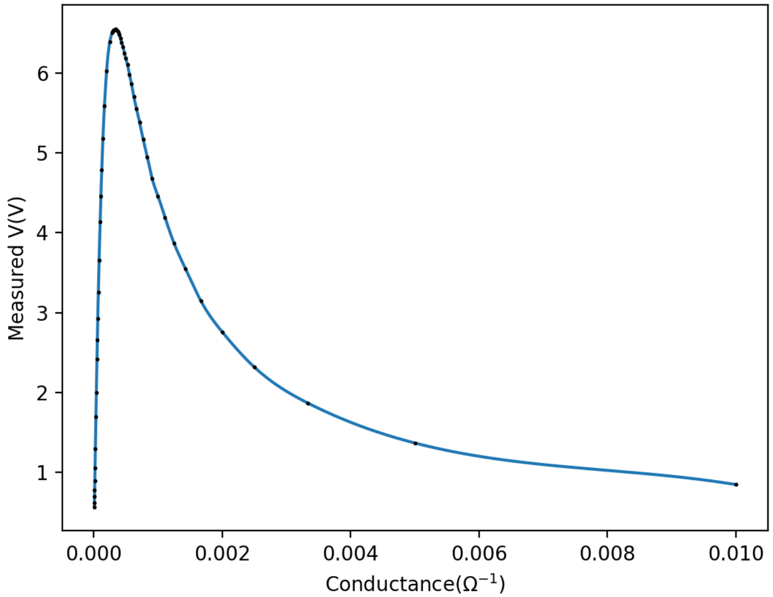
2. Feed in multiple DC gate voltage
    - Every measurement is taken from an optimized signal
    - Time consuming



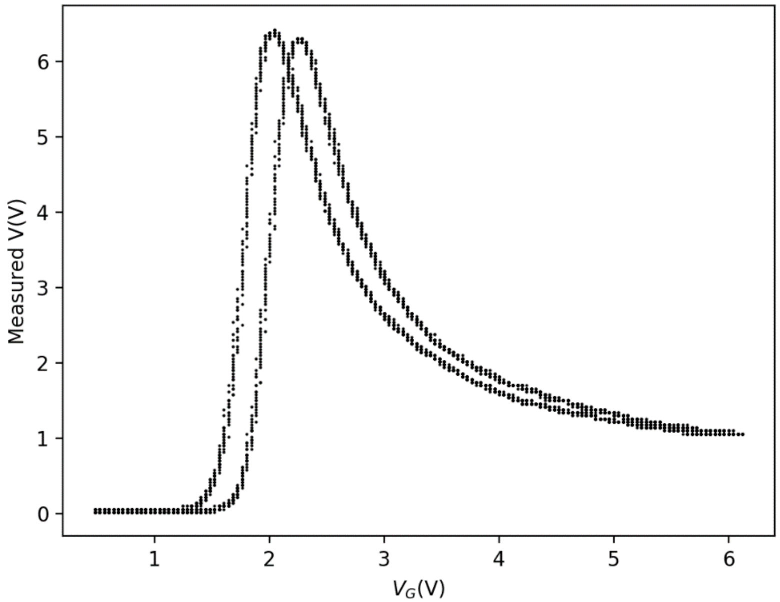
# DISCUSSION AND ADVICE

## Trouble shooting:

Double-valued calibration curve




Hysteresis




Try another lock-in frequency!

This double-value occurs at ~200Hz, we tested that calibration is good at ~90Hz and ~400Hz.

Decrease lock-in time constant!

Too long lock-in o/p integration time (compared to the sweeping frequency of gate voltage) will distort the signal.

**Advice:**
Find a way to make use of digital analog function generator & scope, and take data from PC. This may help improve accuracy and eliminate error in reading.

# THANKS