Compressibility Study of two-dimensional systems

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Plan of this talk

- Introduction
  - What is the compressibility of a 2DEG and what can be learnt from it?
- Structures & Methods
  - single- and double-layer structures
  - capacitance & electric field penetration techniques
- Results & Analysis
  - zero field (negative compressibility)
  - parallel magnetic field (enhanced negative compressibility)
  - perpendicular magnetic field (energy gaps in the density of states)
- Summary & Conclusions

Compressibility

Definition

In a 2DEG the compressibility is defined as $\kappa = \frac{1}{n^2}\left(\frac{dn}{d\mu}\right)$

dn/dm is called the thermodynamic density of states.

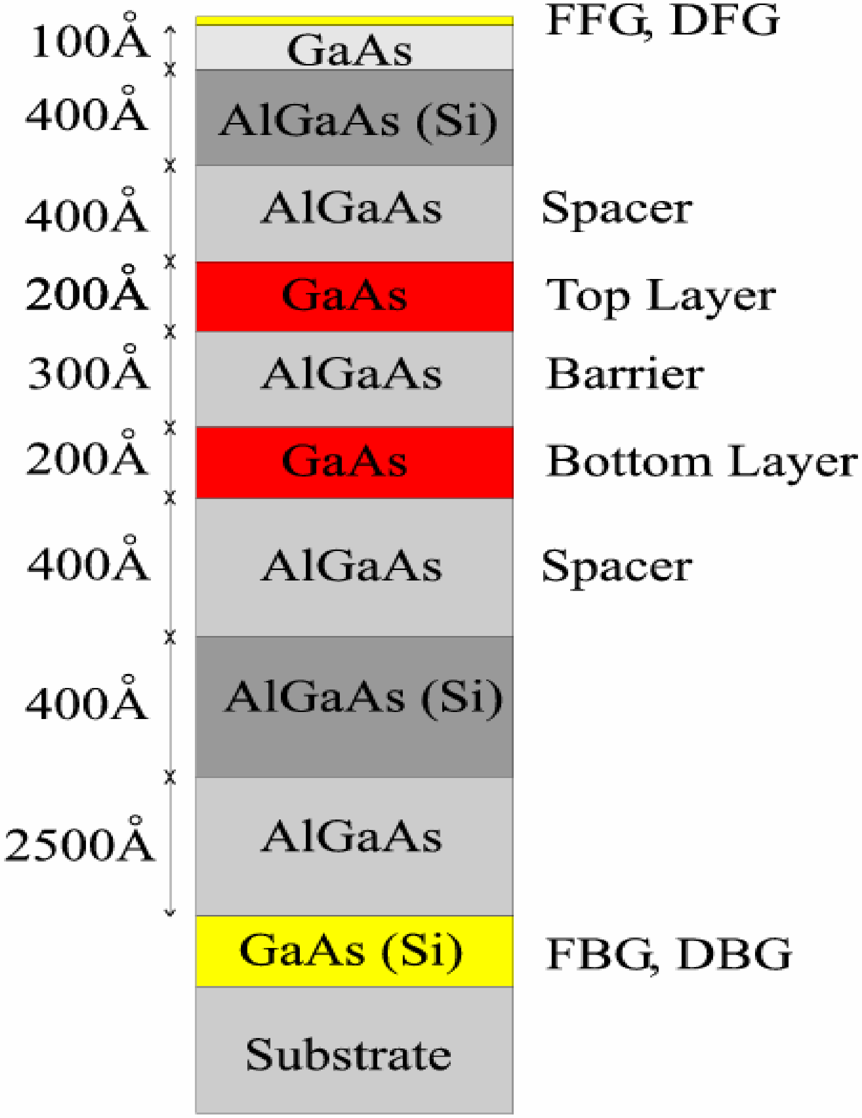
The thermodynamic density of states is the rate of change of the chemical potential with carrier concentration.

Aims

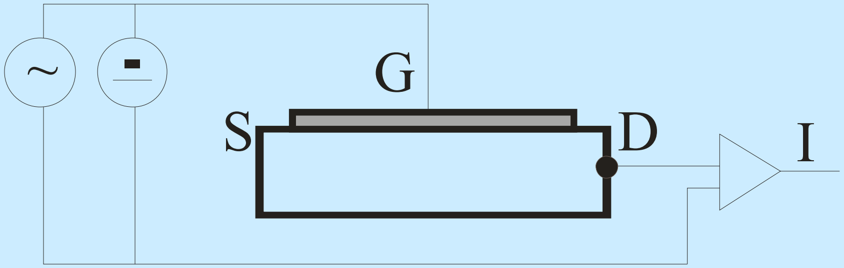
Difference between the thermodynamic and the single particle density of states, $\pi\hbar^2 / m^*$, gives information about electron interactions.

Possible changes of the state of matter may be more evident than in other conventional transport measurements (such as resistance).

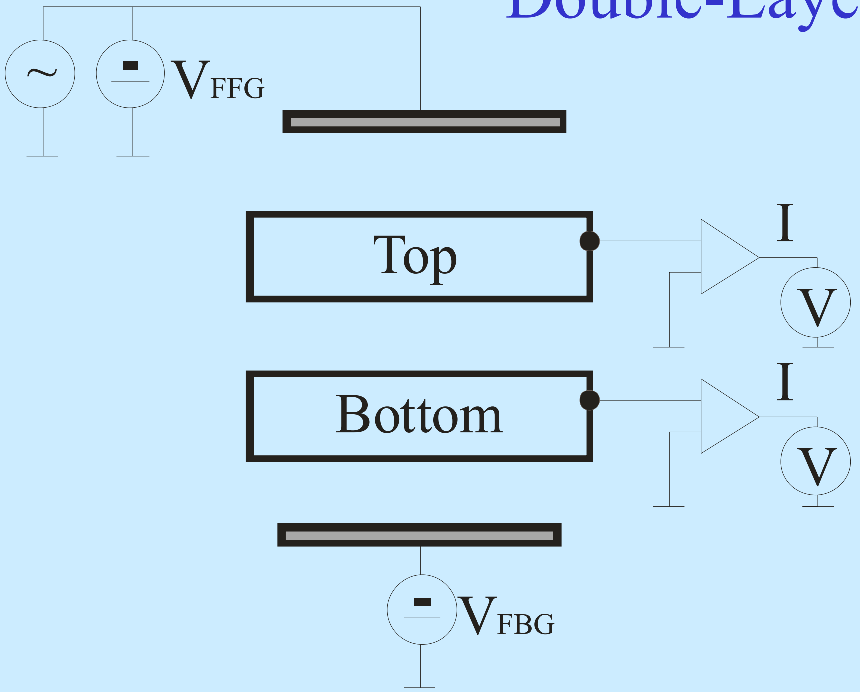
Sample & Circuit



Single-Layer

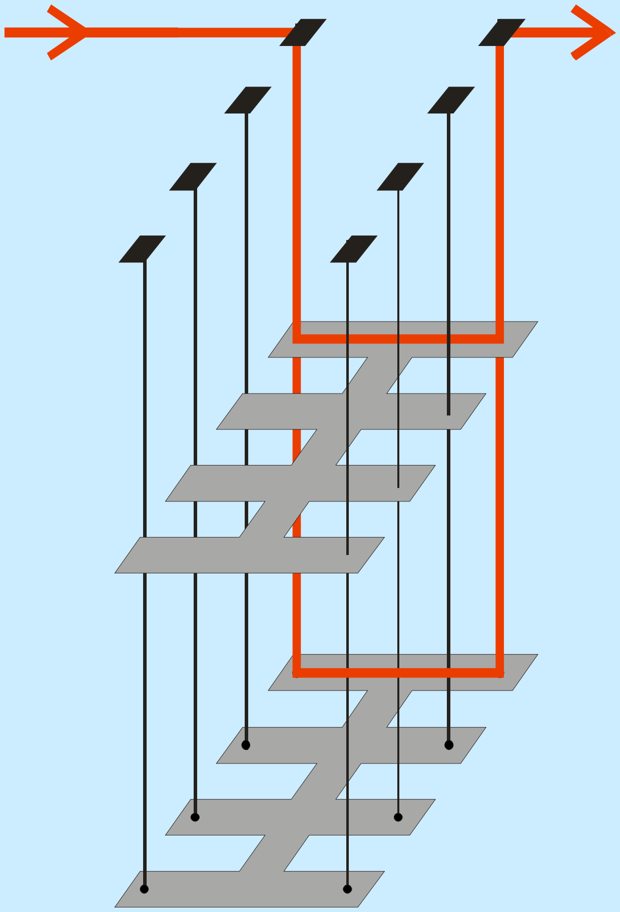


Double-Layer



Defining double-layer structures

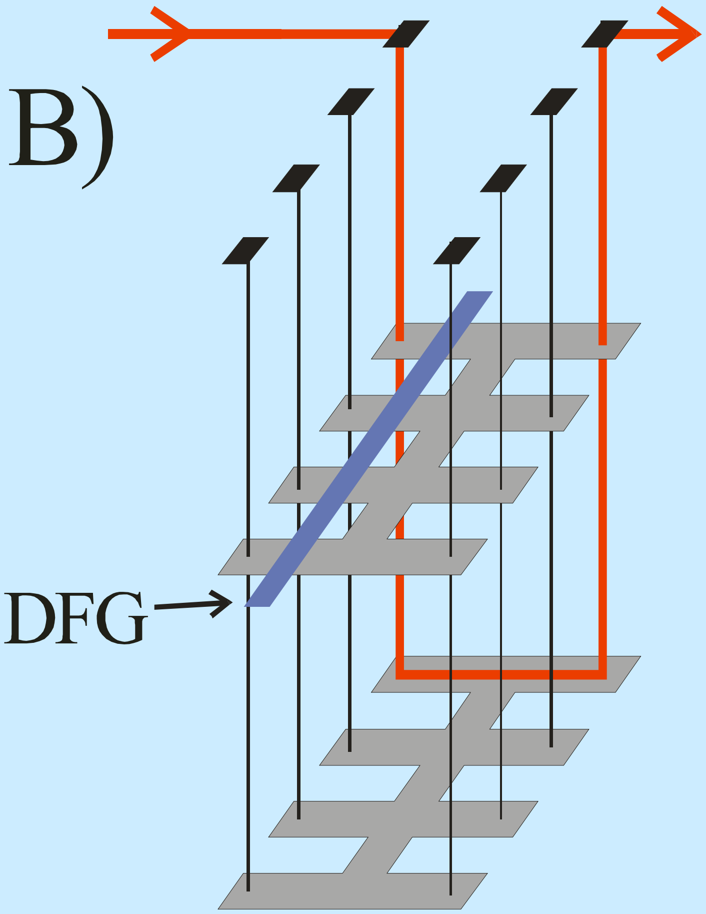
A)



Contacts connect both layers together in parallel - current can flow from left to right via both layers.

Voltages need to be applied to ‘defining gates’ in order that the two layers can be measured independently.

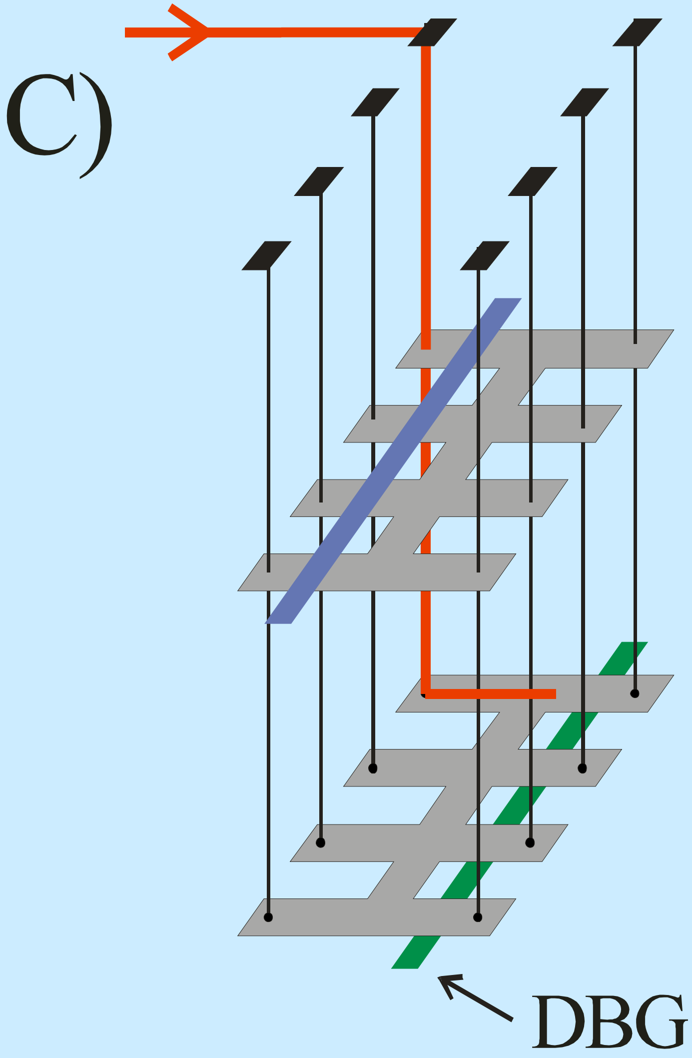
Defining double-layer structures



Voltage is applied to the defining front gate.

Current can only flow from left to right via the bottom layer.

Defining double-layer structures



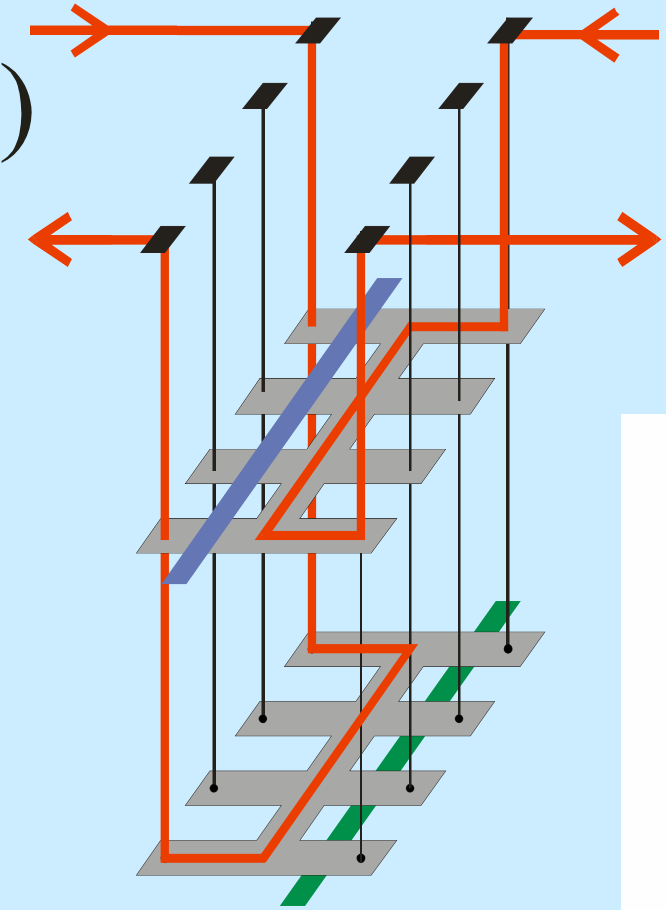
Voltage is applied to the defining back gate.

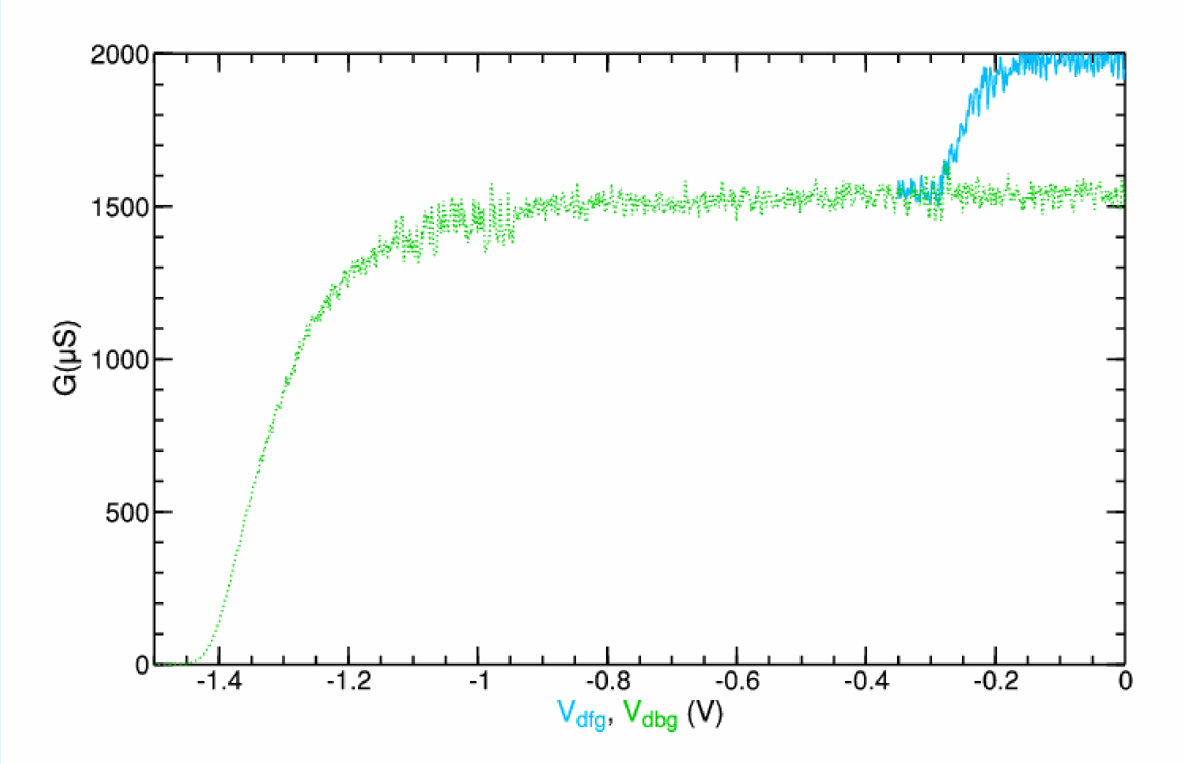
Current can no longer flow from left to right.

Defining double-layer structures

With defining voltages applied the left hand contacts are only connected to the bottom layer, and the right to the top.

D)





Capacitance Method

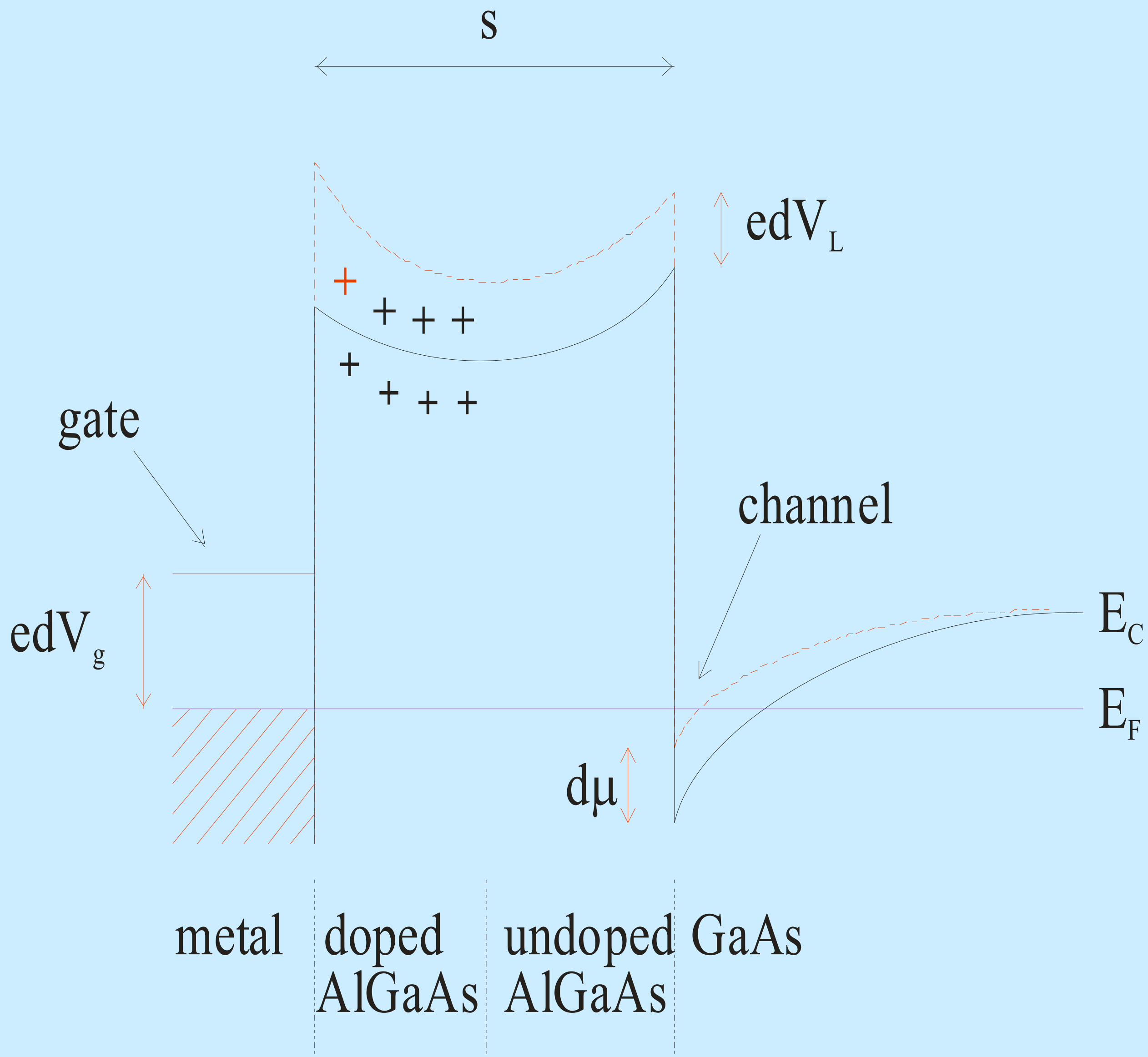
$$deV_g = deV_L + d\mu$$

$$\downarrow$$

$$\frac{deV_g}{dn} = \frac{deV_L}{dn} + \frac{d\mu}{dn}$$

$$\downarrow$$

$$C_T^{-1} = C_L^{-1} + C_E^{-1}$$



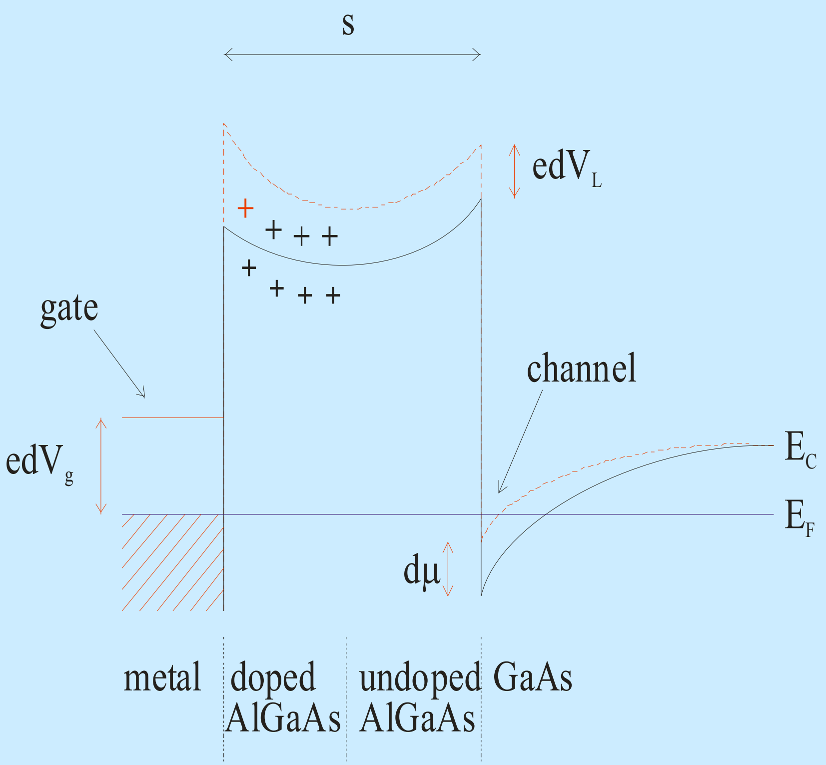
Capacitance Method

Applied voltage, dV_g, results in change of concentration, dn.

C_T gives the concentration.

C_L is important for characterisation: donor concentration, surface potential etc.

C_E is proportional to the compressibility.



Advantage: Simplicity of method for all transistor structures.

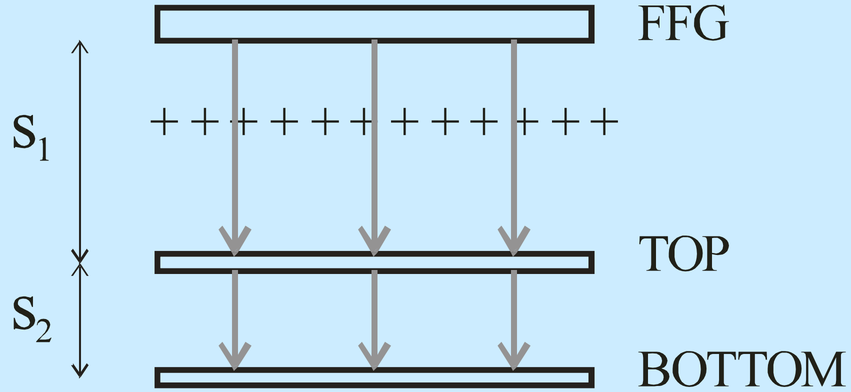
Disadvantage: Difficulty in extracting C_E at high concentration.

$$dV_g = dV_L + d\mu$$

$$C_T^{-1} = C_L^{-1} + C_E^{-1}$$

Penetrating Field Technique

Electric field penetrating through the top layer is proportional to its compressibility. [Eisenstein *et al* PRL **68**, 674(1992)]



Electric field generates a current in the bottom (probe) layer.

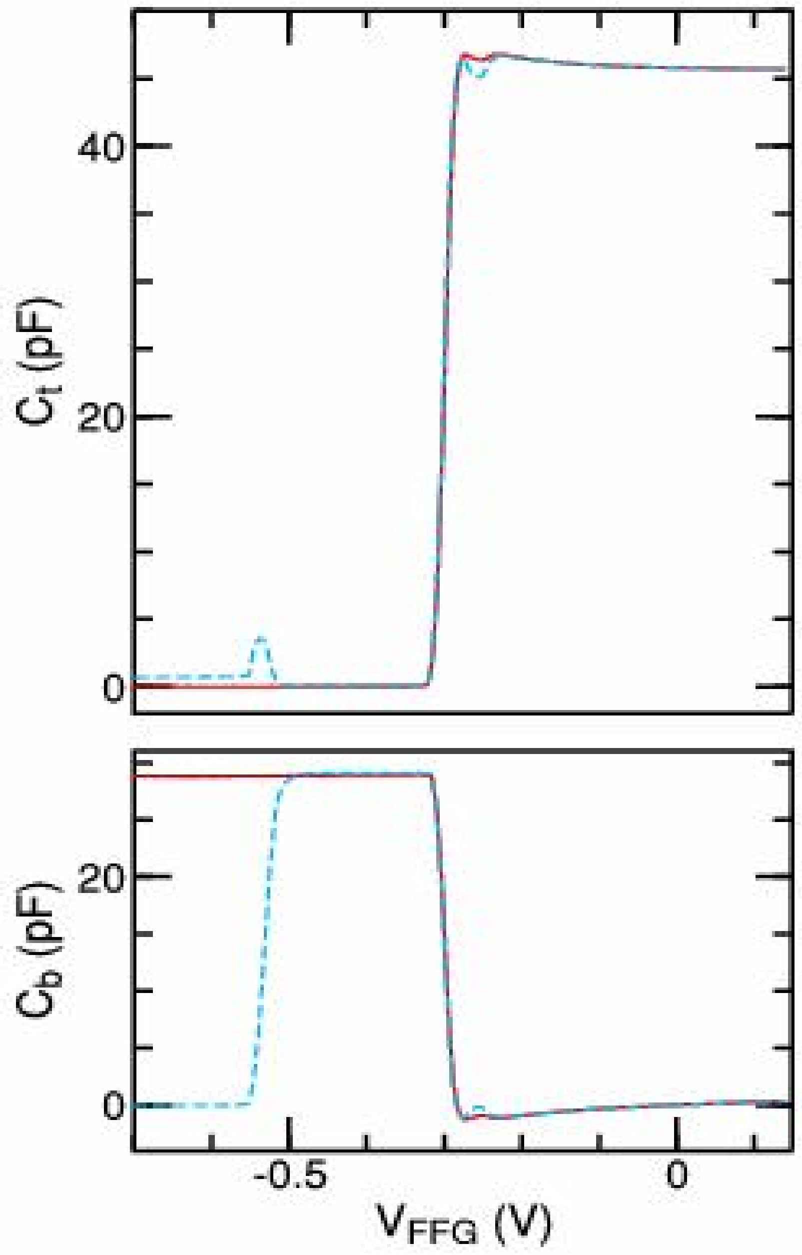
$$\frac{dE_p}{dE_0} = \frac{d_t}{d_t + d_b + s_2}$$

Advantage: Very accurate over entire concentration range.

Disadvantage: Only suitable for structures with a probe layer.

$$d_{t,b} = \left(\frac{\varepsilon_0 \varepsilon_r}{e^2}\right)\left(\frac{d\mu}{dn}\right)_{t,b}$$

Results in zero magnetic field



At large top layer concentration:

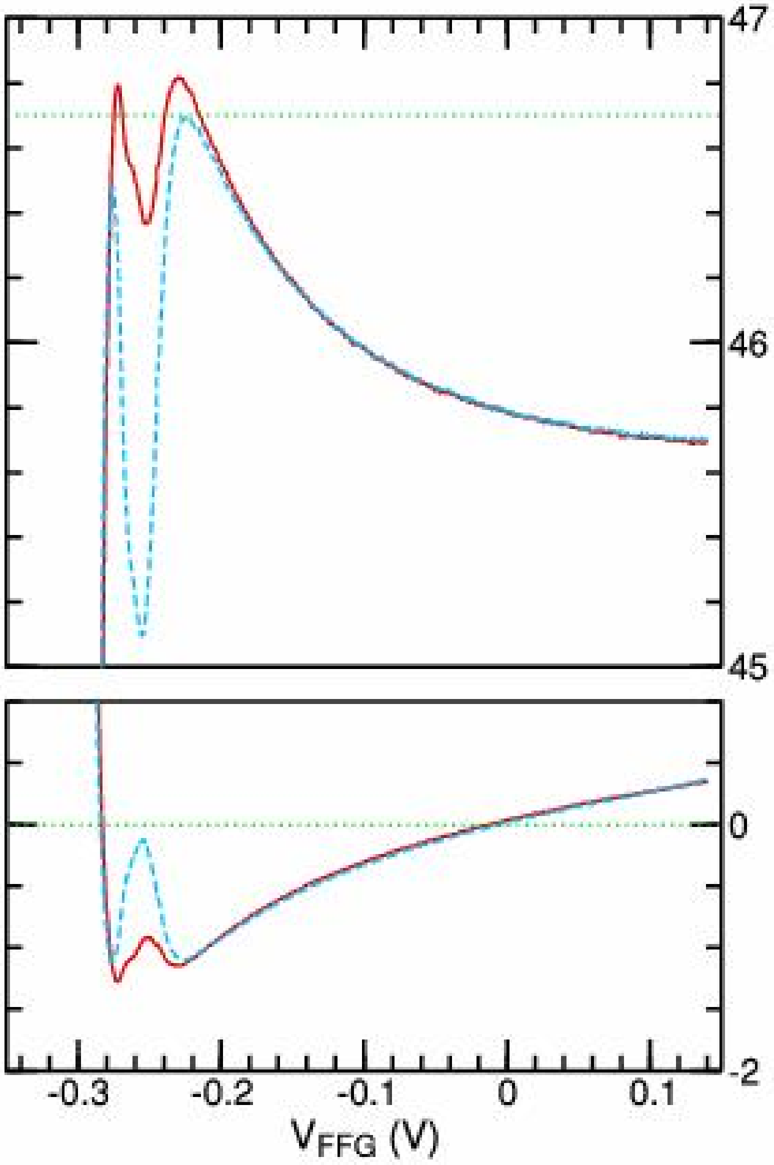
- Top layer capacitance is large as it is dominated by the geometric capacitance.
- Penetrating field is small because the top layer can screen the gate voltage effectively.

At small top layer concentration

- Top layer capacitance decreases as the compressibility decreases.
- Penetrating field reaches a maximum as the top layer cannot screen the gate voltage.

Results in zero field (zoomed in)

- ‘Metallic regime’: Transition from positive to negative compressibility.
  - Capacitance rises above the geometric capacitance level.
  - Penetrating field is negative.
- ‘Insulating regime’: Rapid divergence at small concentration.
  - Capacitance tends to zero.
  - Penetrating field increases to a maximum level.
- Two additional features:
  - Near depletion of top channel (sample dependent but robust feature).
  - Near depletion of bottom channel (possible evidence of negative compressibility of the probe layer).

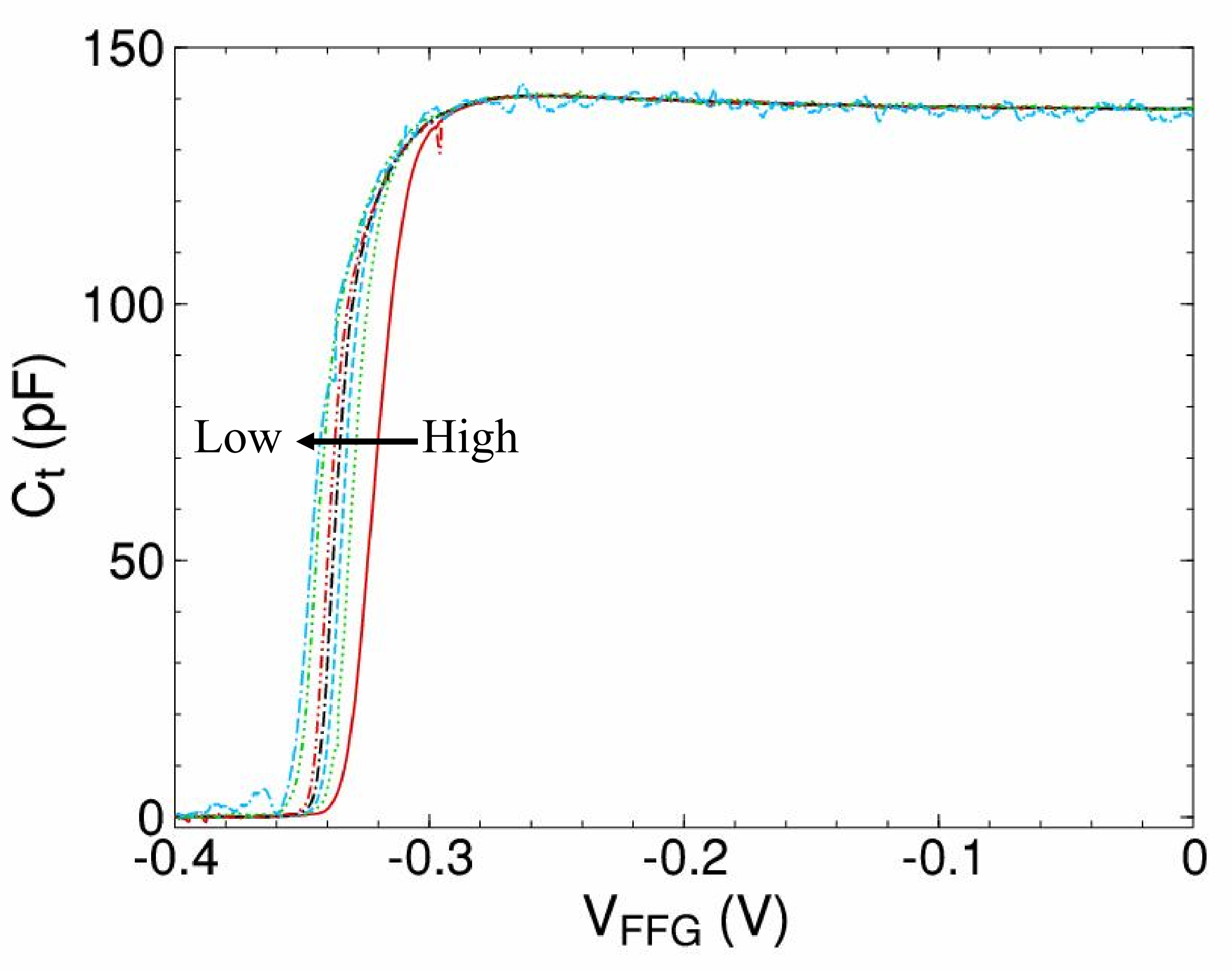


Frequency dependence

Near depletion strong frequency dependence is observed.

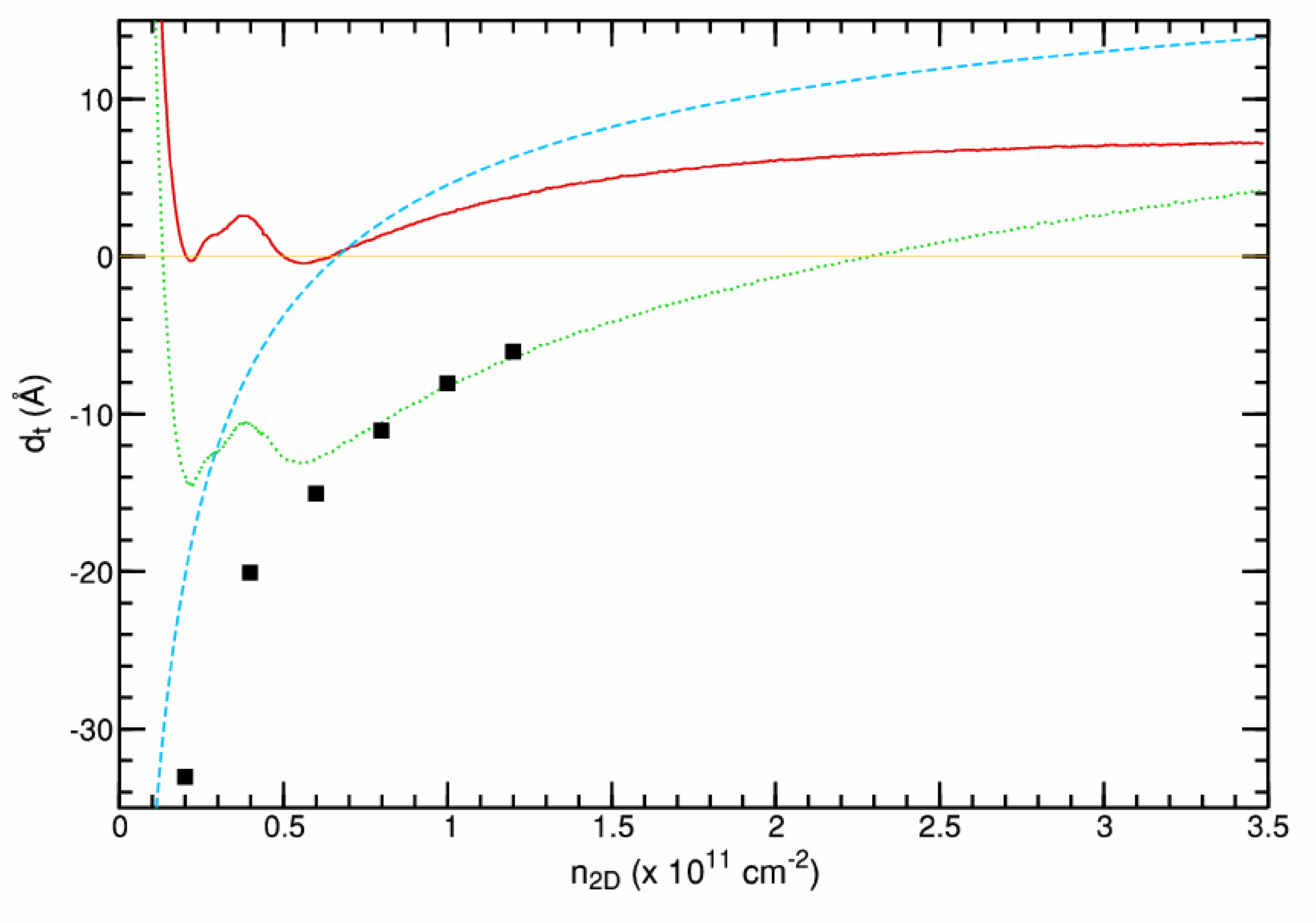
If the frequency is too high not all carriers are involved in the current in the circuit - error in concentration.

Similar temperature dependence also observed.



For a reliable measurement RC must be small.

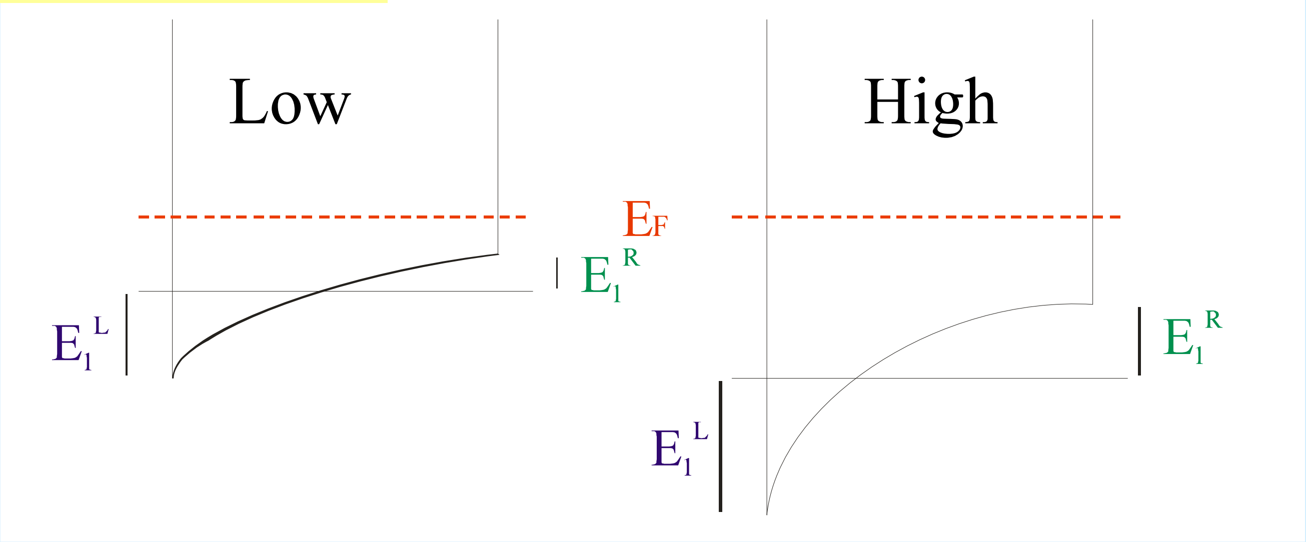
Results as a function of concentration



Difference between methods

The concentration of the 2DEG system is given by, $n = g_{2D}\left[\mu - E_1\right]$

thus $\frac{d\mu}{dn} = \frac{1}{g_{2D}} + \frac{dE_1}{dn}$



The subband moves relative to the conduction band in opposite directions in the two methods.

First approximation is to take the average of the two methods. Second approximation is to make a constant shift to results from penetrating field method.

‘Metallic Regime’

- Non-interacting $\frac{d\mu}{dn} = \frac{1}{g_{2D}} = \frac{\pi\hbar^2}{m^*}$ (kinetic term)
- Exchange interactions (Hartree-Fock theory)

$$E = \left[\frac{1}{r_s^2} - \frac{8\sqrt{2}}{3\pi}\frac{1}{r_s}\right]n$$

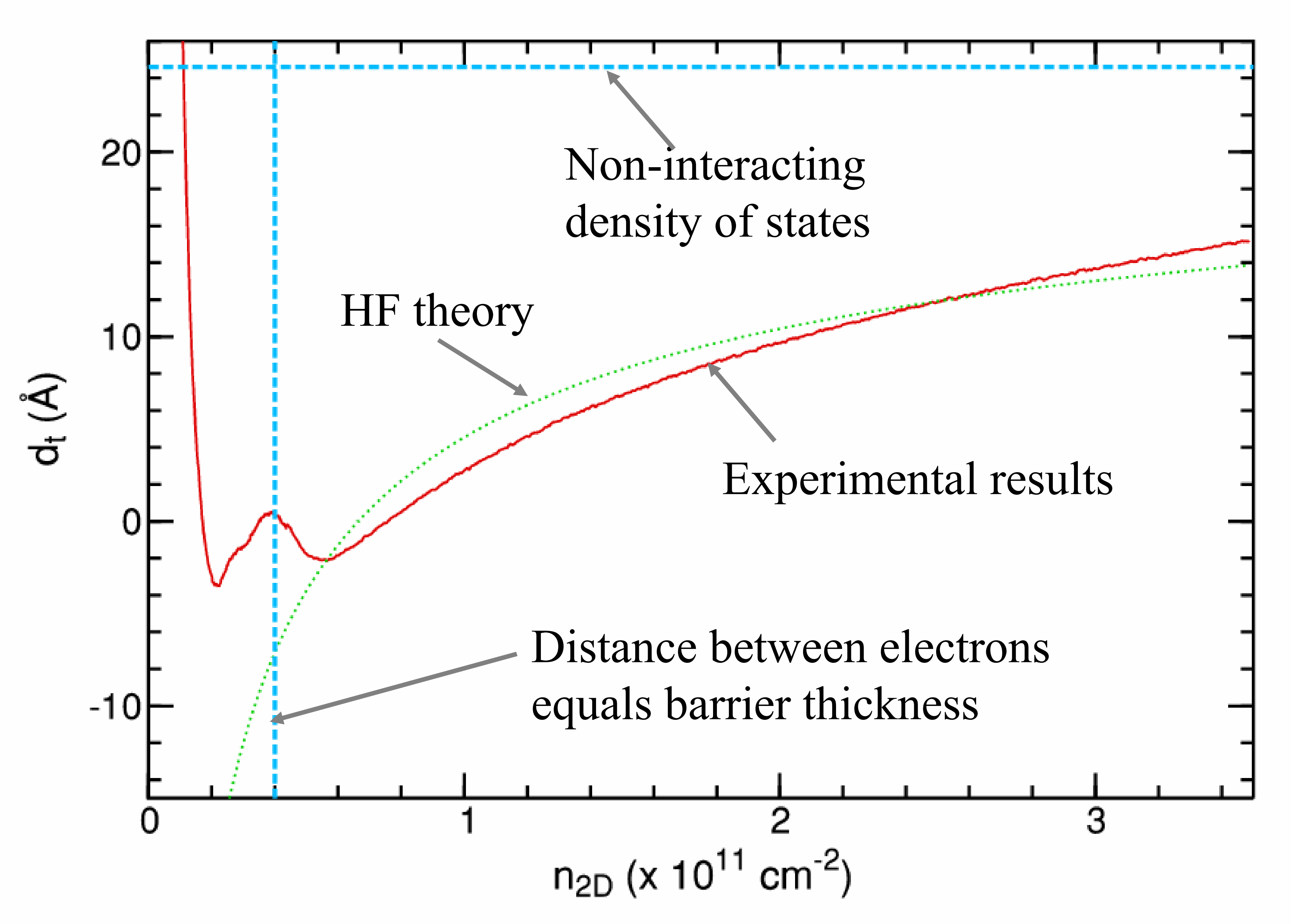
c.g.s. [Nagano *et al* PRB **29,** 1209, (1984)]

$$\frac{d\mu}{dn} = \frac{\pi\hbar^2}{m^*} - \left(\frac{2}{\pi}\right)^{1/2}\left(\frac{e^2}{4\pi\varepsilon_0\varepsilon_r}\right)n^{-1/2}$$

SI

  - Compressibility is negative at small concentrations!
- Correlation energy is also negative, but negligible.
- Thickness of layer reduces the coulomb interaction between carriers, which reduces the effect of negative compressibility.

Results as a function of concentration



Non-interacting density of states

HF theory

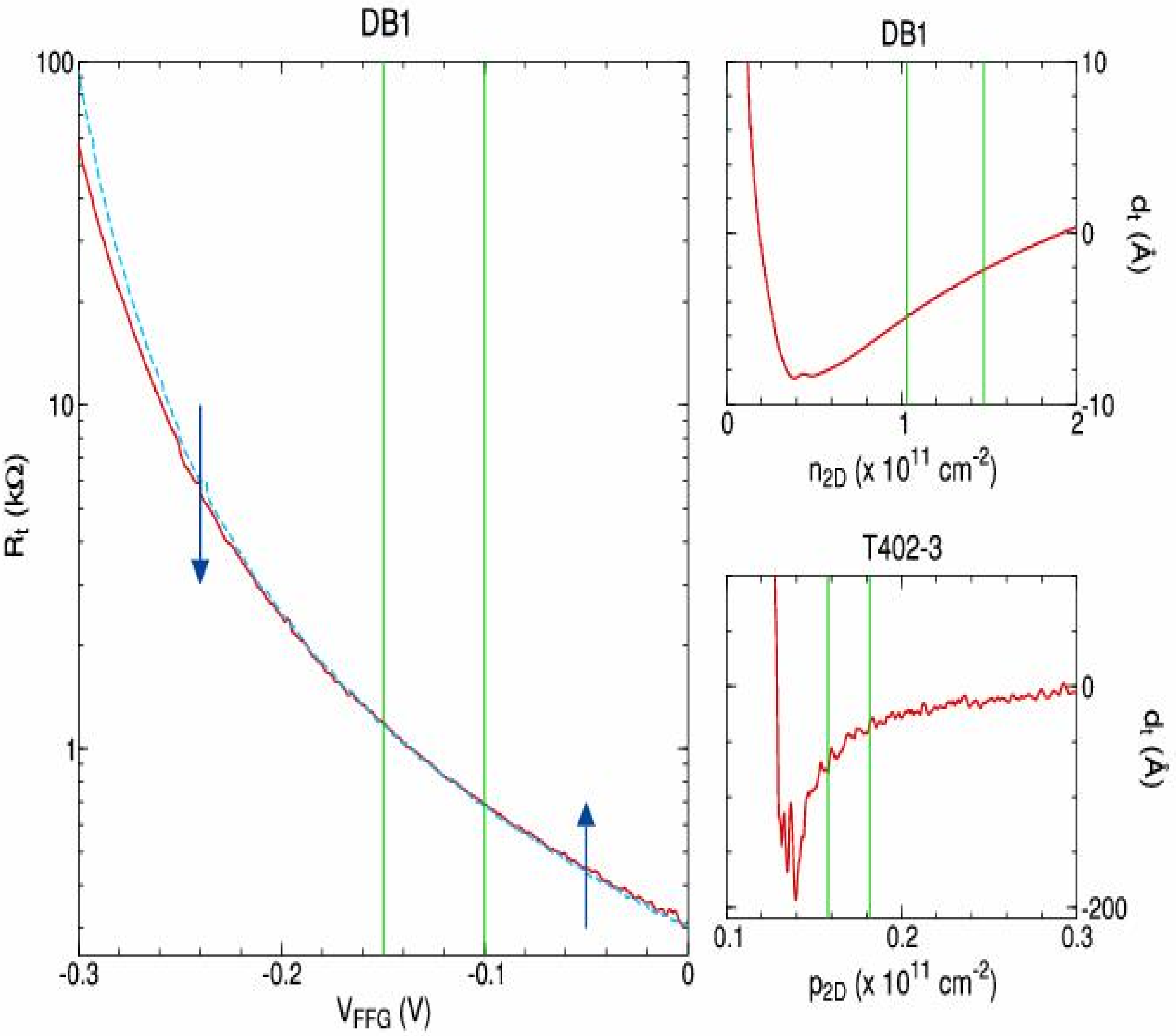
Experimental results

Distance between electrons equals barrier thickness

‘Metal-to-Insulator Transition’

In both n and p-type GaAs the temperature dependence of the resistance reverses its sign.

In neither n or p-type GaAs is there any feature in the compressibility at this concentration.



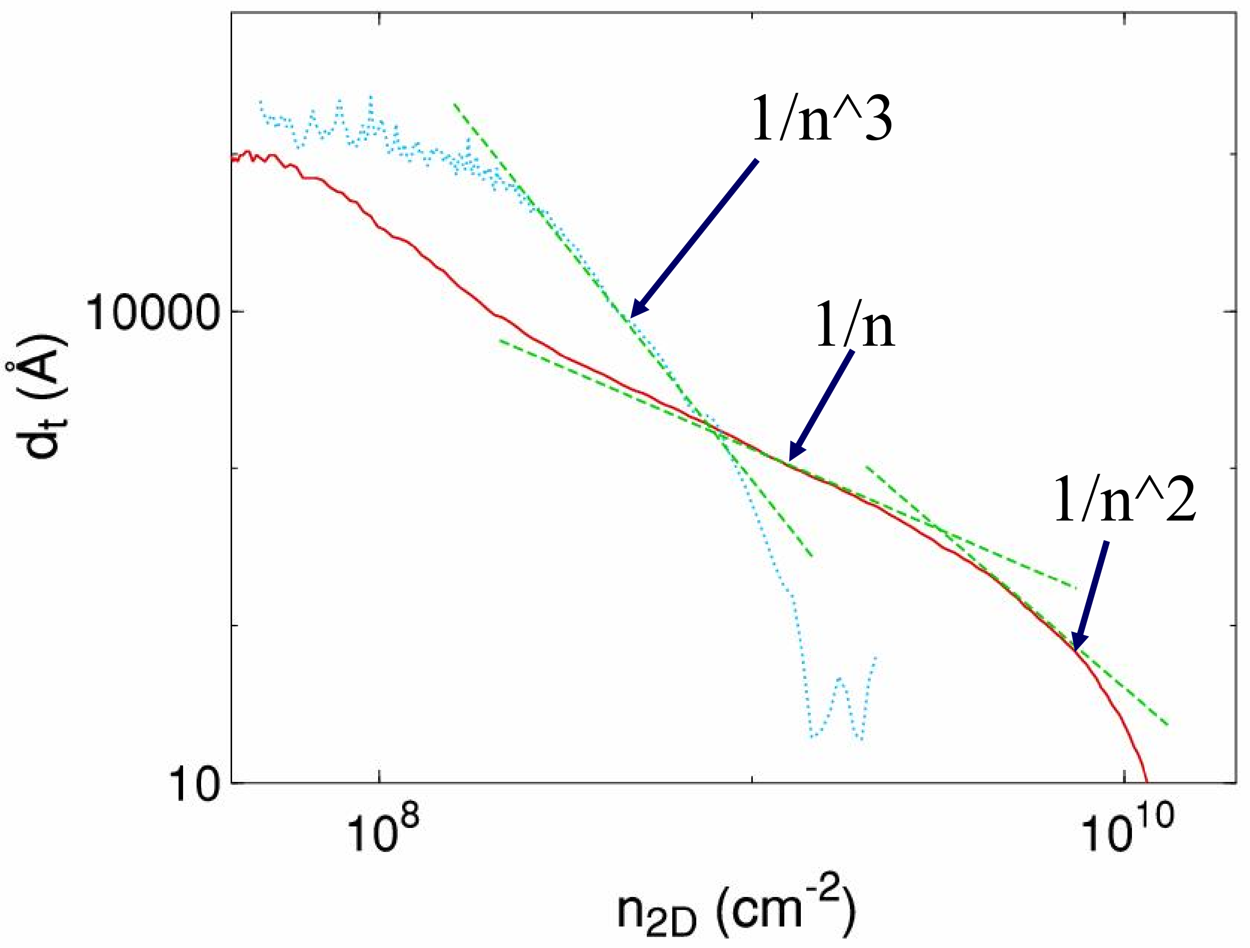
Rapid divergence

At small concentration dm/dn rapidly diverges from Hartree-Fock theory.

Strongly frequency and temperature dependent.

n-GaAs: 1/n and 1/n^2 dependence.

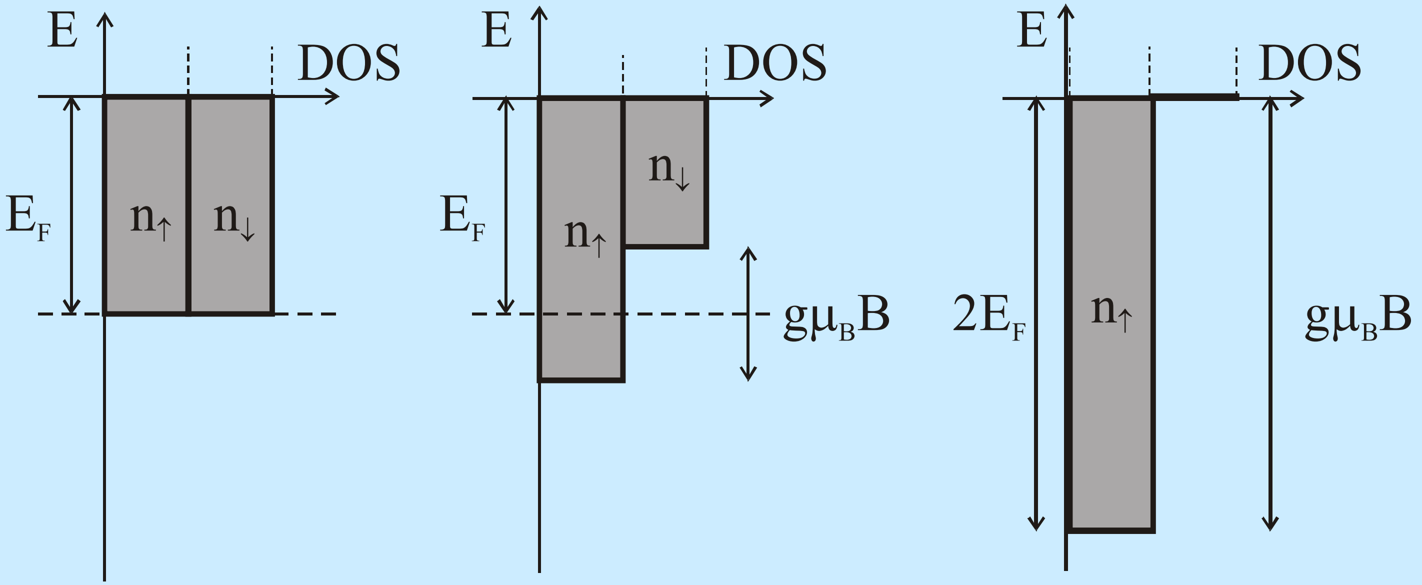
p-GaAs: 1/n^3 dependence.



Results in Parallel Magnetic Field

Parallel magnetic field polarises electron spin

Non-interacting picture



[Cooper (private communications), Bulutay *et al* PRB **65**, 195116, (2002)]

$$\frac{d\mu}{dn} = 2\frac{\pi\hbar^2}{m^*} - \sqrt{2}\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{e^2}{4\pi\varepsilon_0\varepsilon_r}\right)n^{-1/2}$$

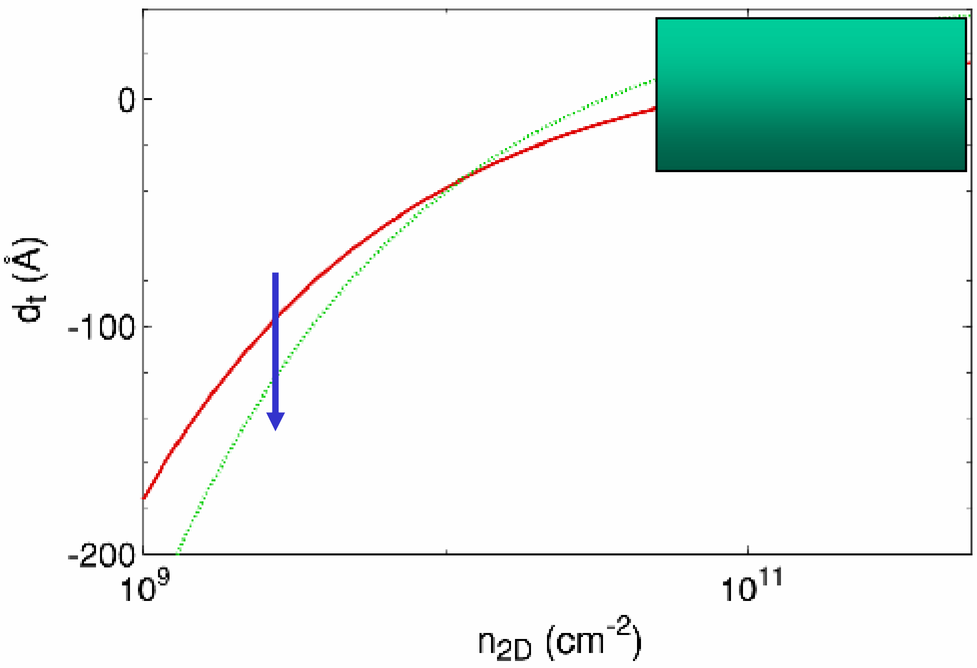
Kinetic term increases.

Exchange interaction term increases.

Results in Parallel Magnetic Field

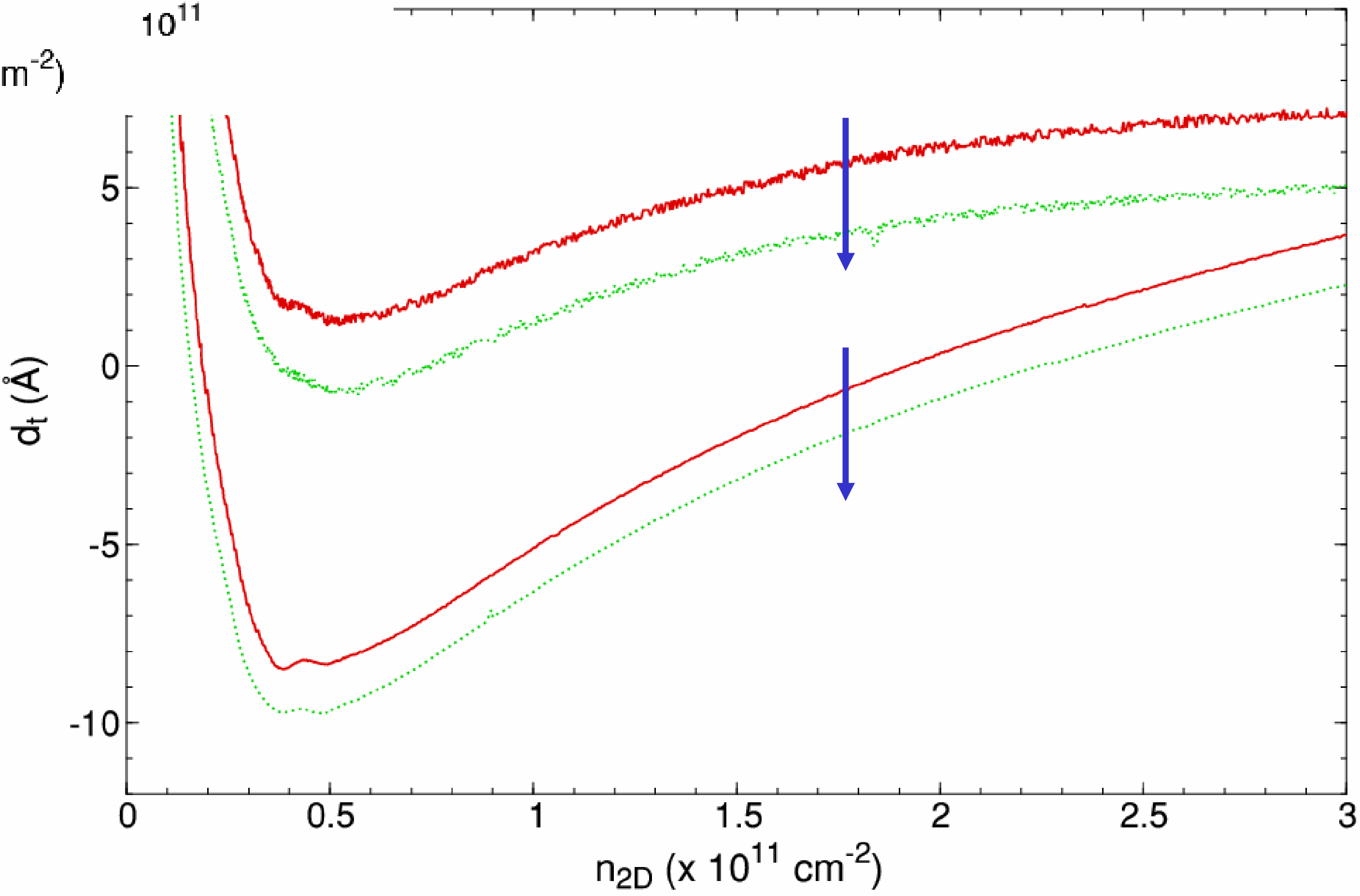
Theory predicts dm/dn to

- Increase for $n > 10^{11}$
- Decrease for $n < 10^{11}$



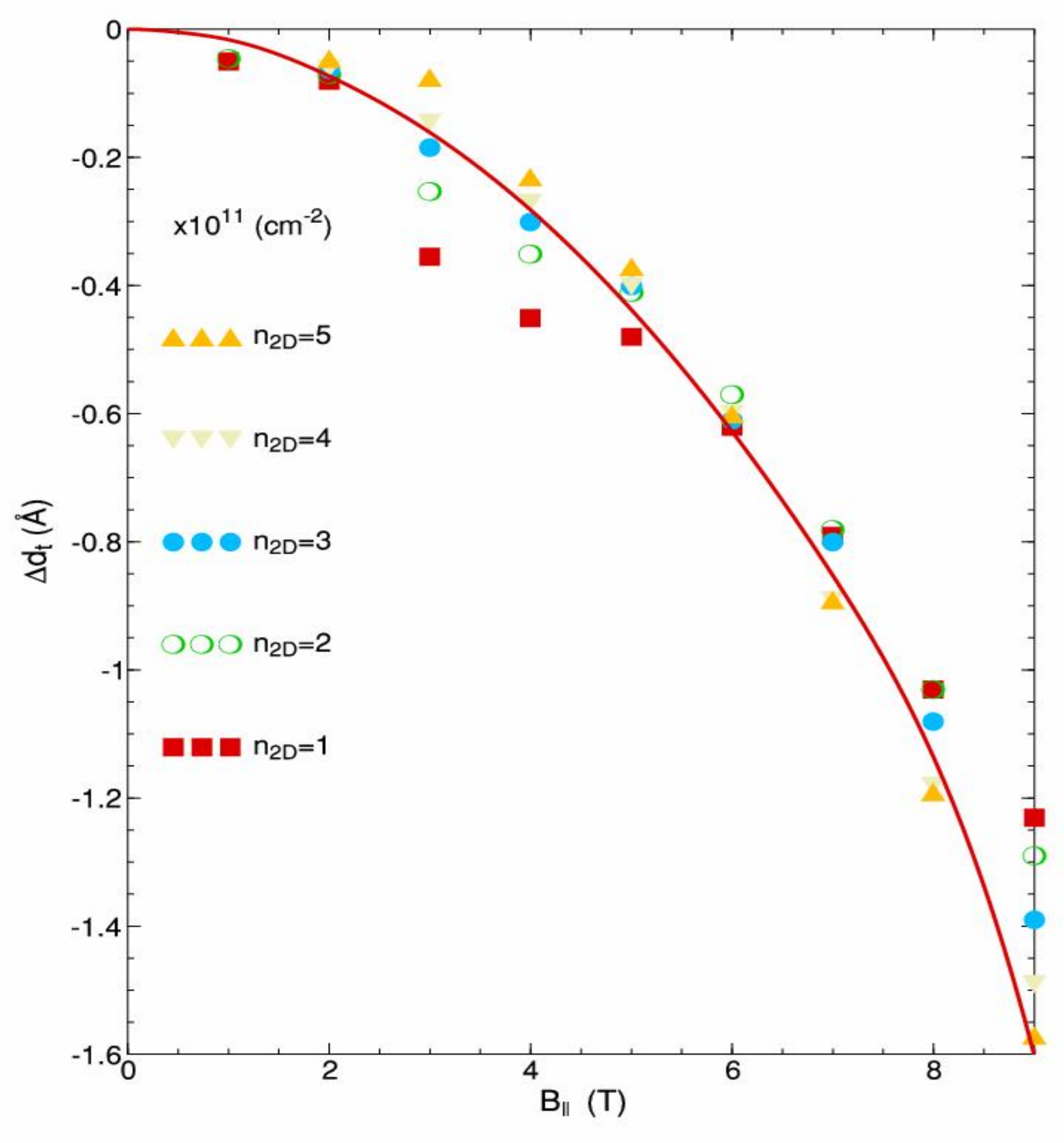
Result is in opposite direction to (and much greater than) expectation.

- Exchange is stronger?
- Low field limit (only partially polarised)

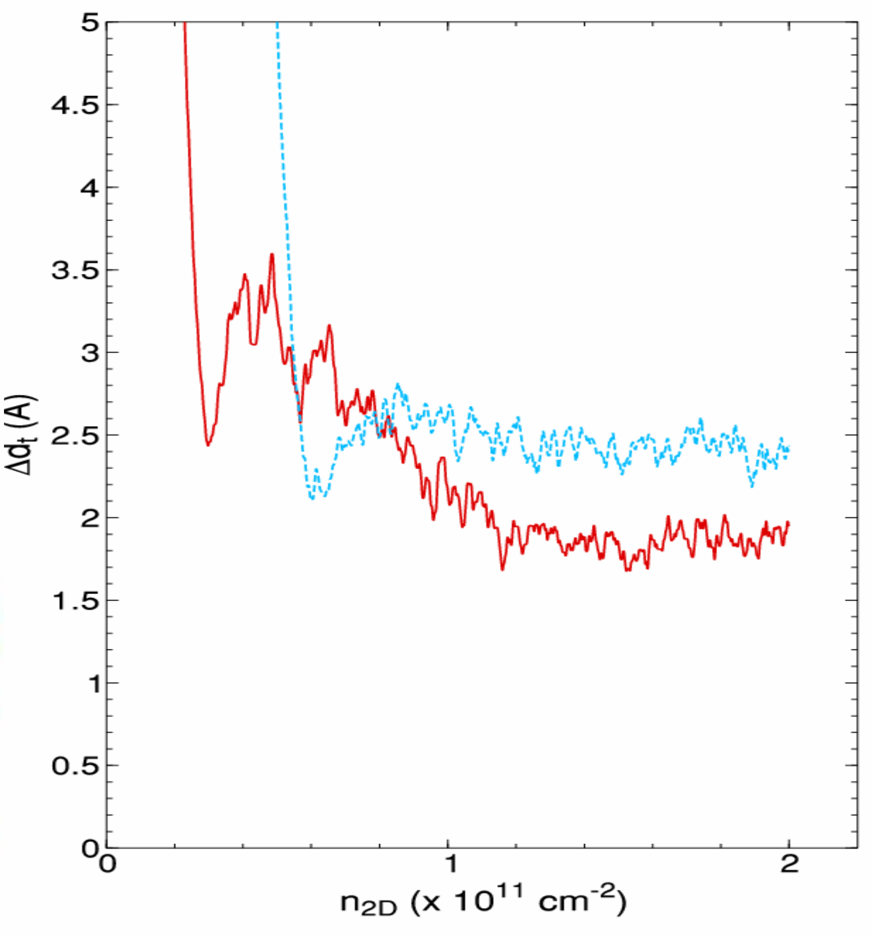


Results in parallel field

Parabolic dependence



Weakly dependent on concentration of either ‘active’ or ‘probe’ layer.

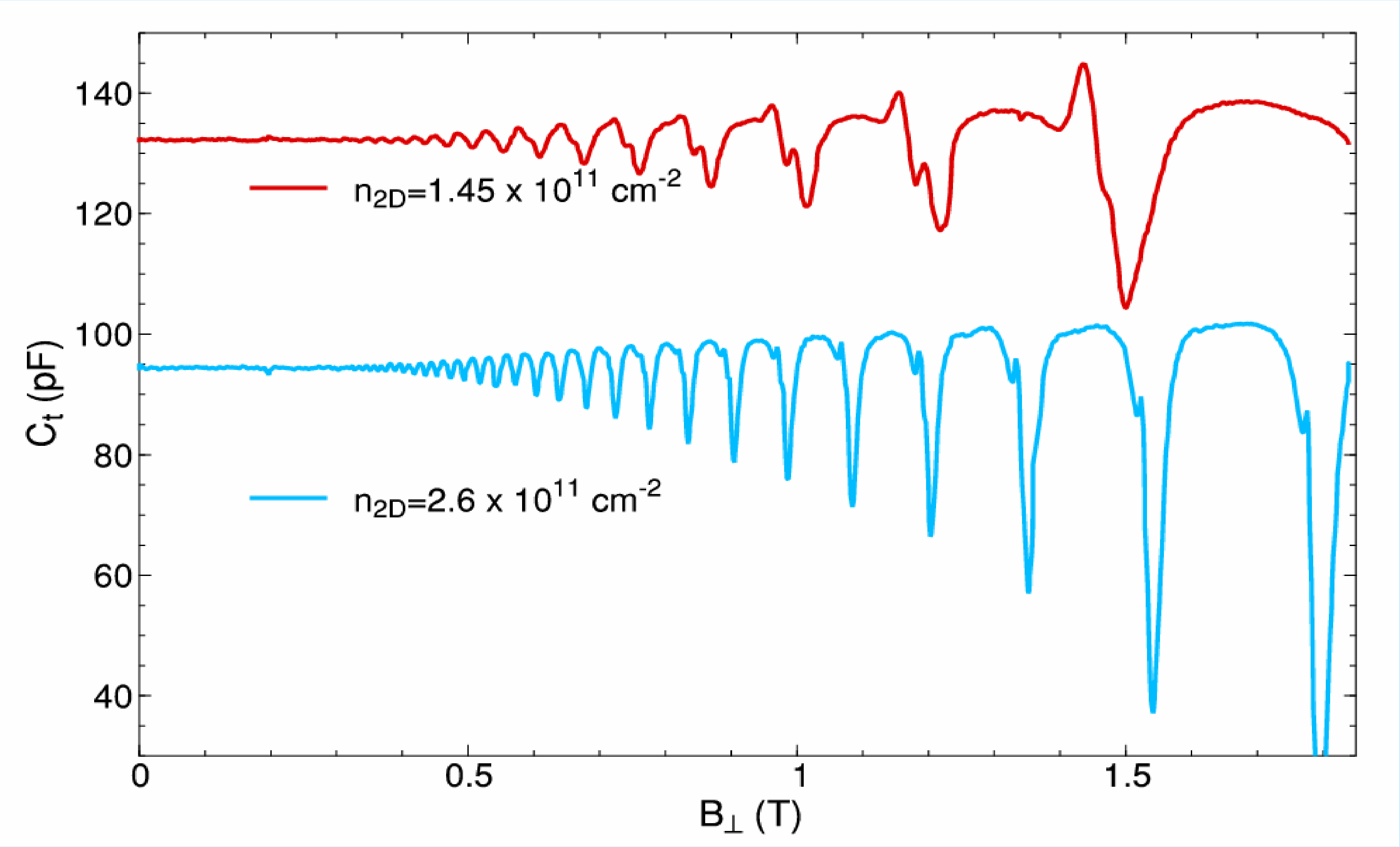


Results in perpendicular magnetic field

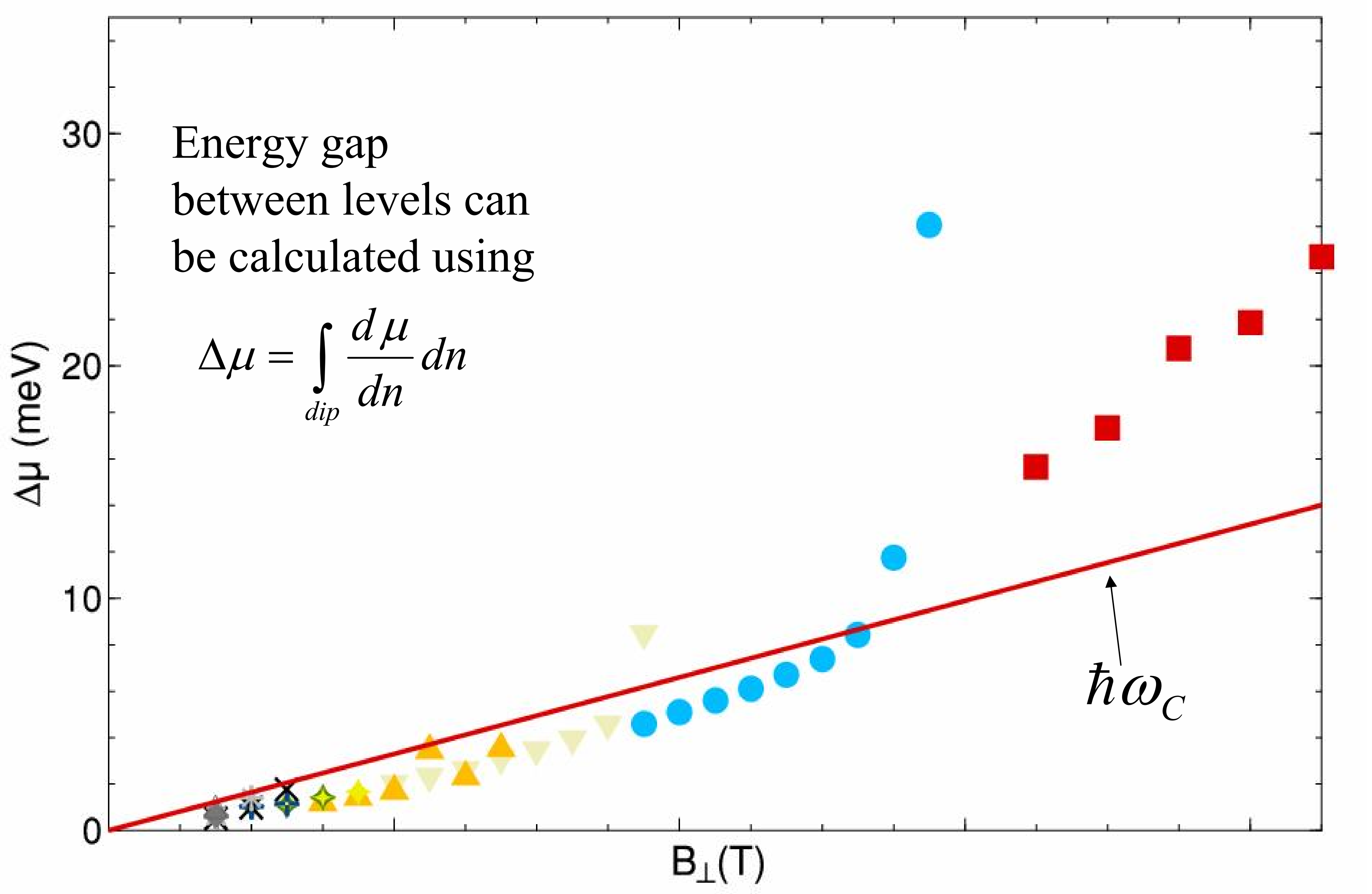
- A magnetic field quantises the density of states.
- Seen in both capacitance and penetrating field techniques.
- Near the tail of Landau levels pronounced features are seen.

Results in perpendicular field

- Dips in the density of states between Landau levels seen in the capacitance.
- Other pronounced peaks and dips seen near fractional states.



Results in perpendicular magnetic field



Energy gap between levels can be calculated using

$$\Delta\mu = \int_{dip} \frac{d\mu}{dn} dn$$

Summary

- Powerful method to investigate:
  - Interactions (exchange and correlation)
  - Effective mass and g-factor (perpendicular field)

- Negative compressibility.
  - Due to electron exchange interaction.
  - Observed using both techniques.

- Rapid divergence from Hartree-Fock theory at small concentrations.
  - Due to disorder?

- Enhanced (?) negative compressibility in parallel magnetic field.
  - Effect opposite and much stronger than predicted.