Mid-term course evaluation

From today until Sunday March 23th at midnight:

Indicative Student Feedback on Teaching

More info: https://www.epfl.ch/education/teaching/fr/soutien-a-lenseignement/ressources-etudiants/#indicativefeedback

From ~ June:

In-depth evaluation

Class 07
Charge transport in semiconductors

17.03.2025

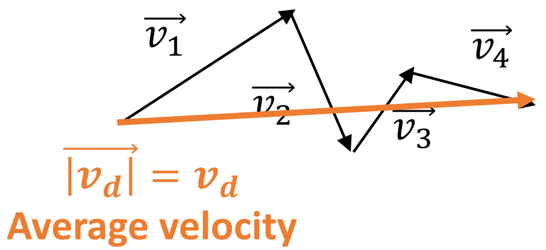
- ❑ Charge mobility
    - Relaxation time approximation
    - Scattering phenomena
    - Matthiesen’s rule
- ❑ 2DEG
    - Engineering 1D channel
    - Quantum conductance

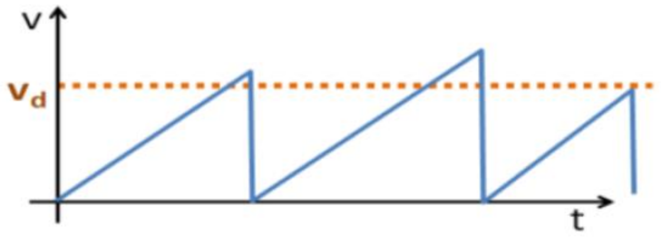
Grundmann, Chapter 8

Drude model for electron gas

Electron transport in an electron gas

$$\vec{F} = -e\vec{E} = \hbar\frac{d\vec{k}}{dt} = m_e\frac{d\vec{v}}{dt}$$





$$\vec{J}_{drift} = -e * n * \vec{v}_d$$ Current density vs average velocity

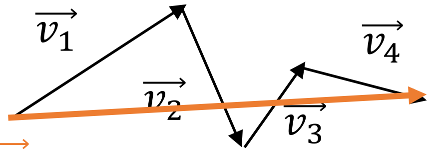
$$\vec{v}_d = \mu_e\vec{E}$$ Average velocity vs electric field

$$\vec{J}_{drift} = -e * n * \mu_e\vec{E}$$ Current density vs electric field

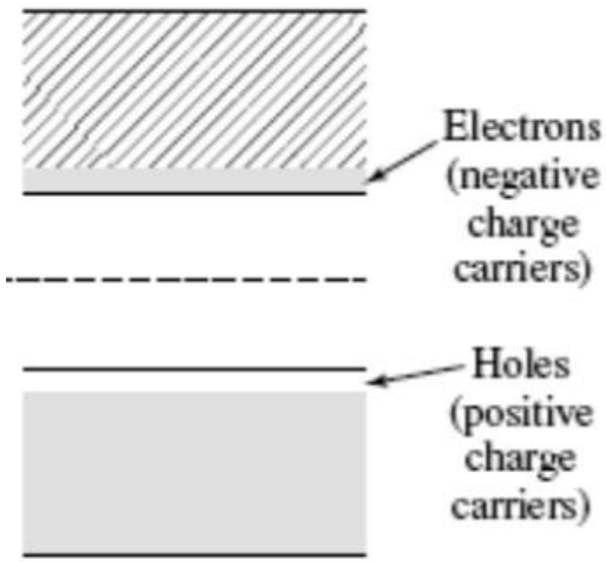
Modified Drude model for semiconductors

Electron transport in a semiconductor

$$\vec{F} = -e\vec{E} = \hbar\frac{d\vec{k}}{dt} = m^*\frac{d\vec{v}}{dt}$$



$|\vec{v_d}| = v_d$
Average velocity



$$\vec{J}_{drift} = -e * n * \vec{v}_{d,e} + e * p * \vec{v}_{d,h}$$

Current density vs average velocity

$$\vec{v}_{d,e} = \mu_e\vec{E} \qquad \vec{v}_{d,h} = \mu_h\vec{E}$$

Average velocity vs electric field

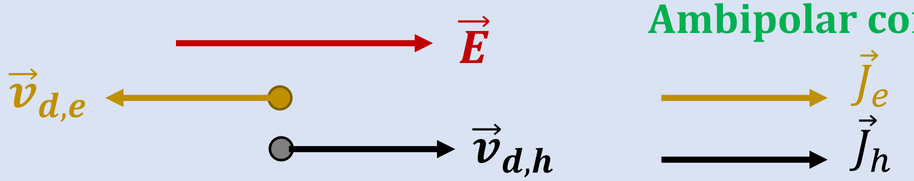
$$\vec{J}_{drift} = -e * n * \mu_e\vec{E} + e * p * \mu_h\vec{E}$$

Current density vs electric field

$$J_{drift} = e * \underbrace{(n * \mu_e + p * \mu_h)}_{\sigma} * E$$

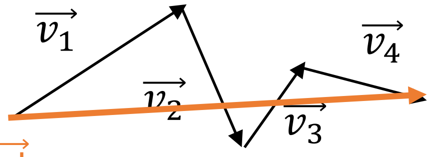
σ: conductivity

Ambipolar conduction



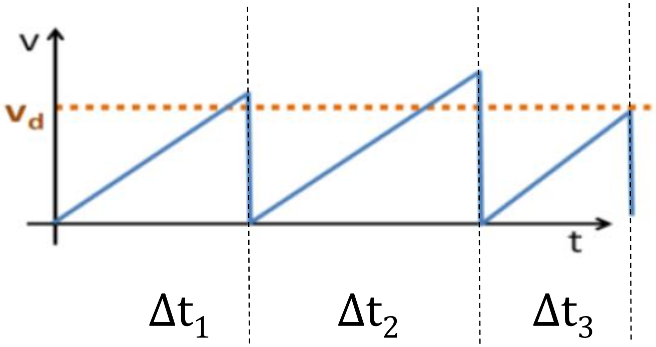
Relaxation time approximation

$$\vec{F} = -e\vec{E} = \hbar\frac{d\vec{k}}{dt} = m^*\frac{d\vec{v}}{dt}$$



$|\overrightarrow{v_d}| = v_d$

Average velocity



$\Delta t_{av} = \tau$

Average time between collision events (scattering)

$\frac{1}{\tau} \rightarrow$ **scattering frequency**

(proportional to the scattering probability)

RELAXATION TIME APPROXIMATION

$$\frac{dv}{dt} = \frac{v_d}{\tau}$$

$$-eE = m^*\frac{v_d}{\tau}$$

$$v_d = -\frac{e\tau}{m^*}E$$

$$\mu = -\frac{e\tau}{m^*} \qquad \sigma = -\frac{e^2 n\tau}{m^*}$$

Question:

Which law of classical physics would not be valid without collisions? Is it physically possible to achieve it?

Mobility of real materials

Material		$-\mu_n$ (cm^2/Vs)	μ_p (cm^2/Vs)
Si	**(1.12 eV)**	1300	500
Ge	**(0.67 eV)**	4500	3500
GaAs	**(1.42 eV)**	8800	400
GaN	**(3.40 eV)**	300	180
InSb	**(0.17 eV)**	77 000	750
InAs	**(0.36 eV)**	33 000	460
InP	**(1.34 eV)**	4600	150
ZnO	**(3.37 eV)**	230	8

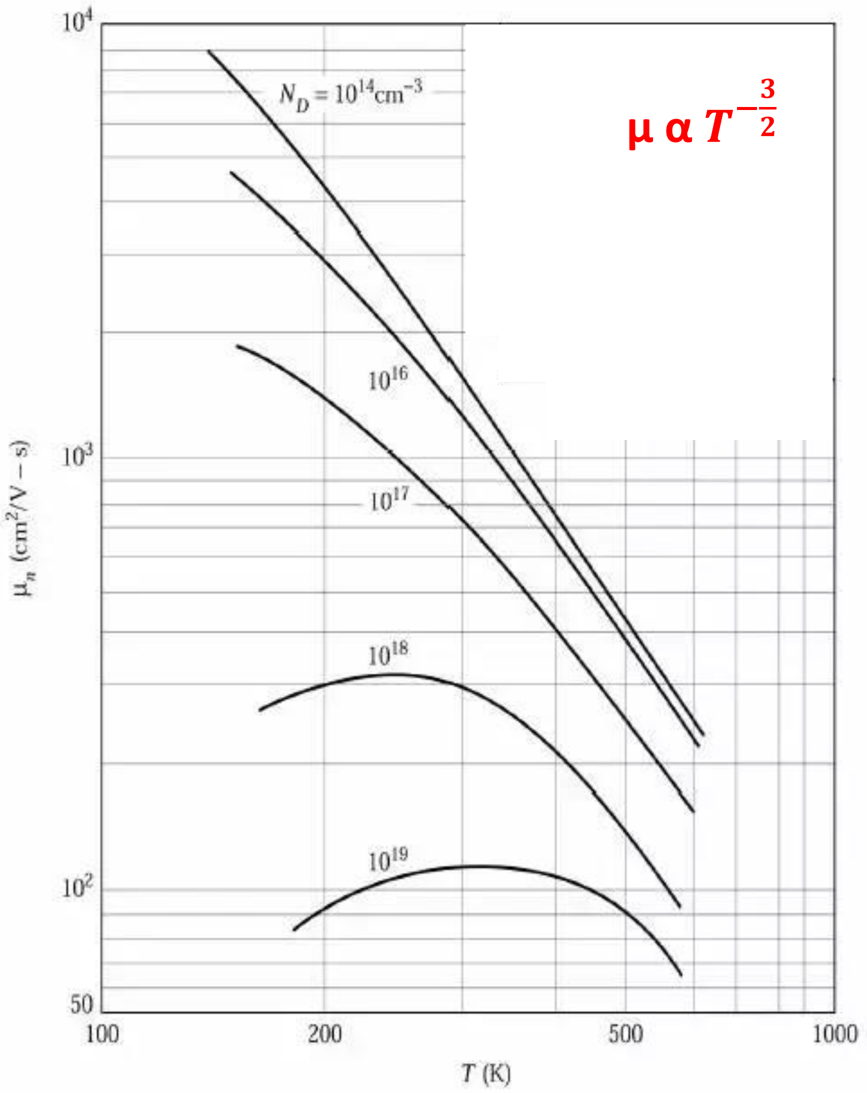
Is the band gap affecting the mobility?
If so, can you explain why?

How would you engineer the charge transport in a semiconductor?

Scattering source

How many scattering phenomena in a crystal can you think of?

Lattice phonons (non-polar)



$\mu \, \alpha \, T^{-\frac{3}{2}}$

Ionized impurities

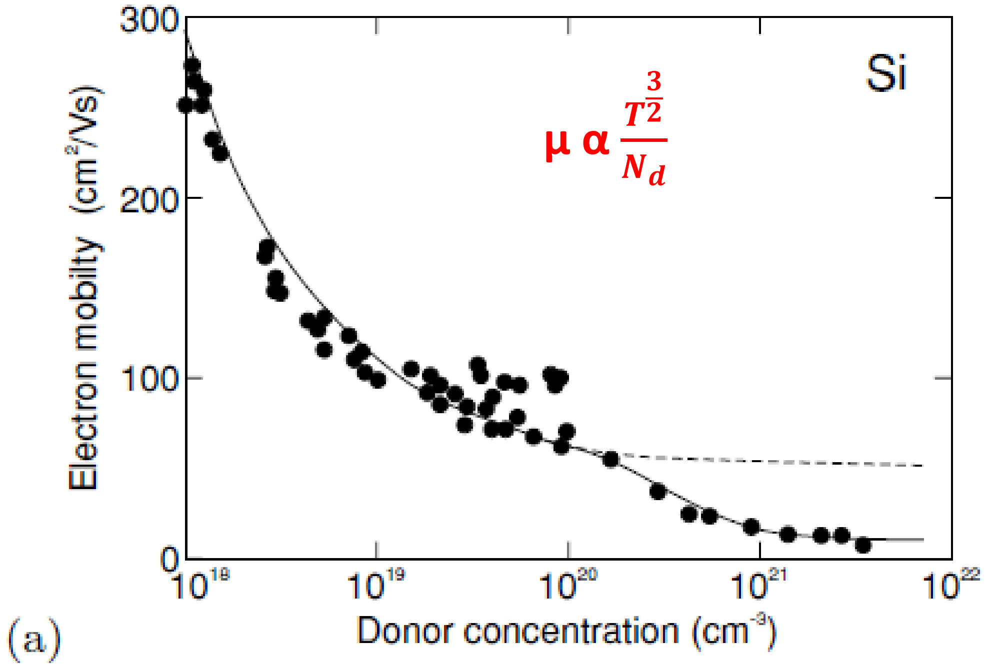
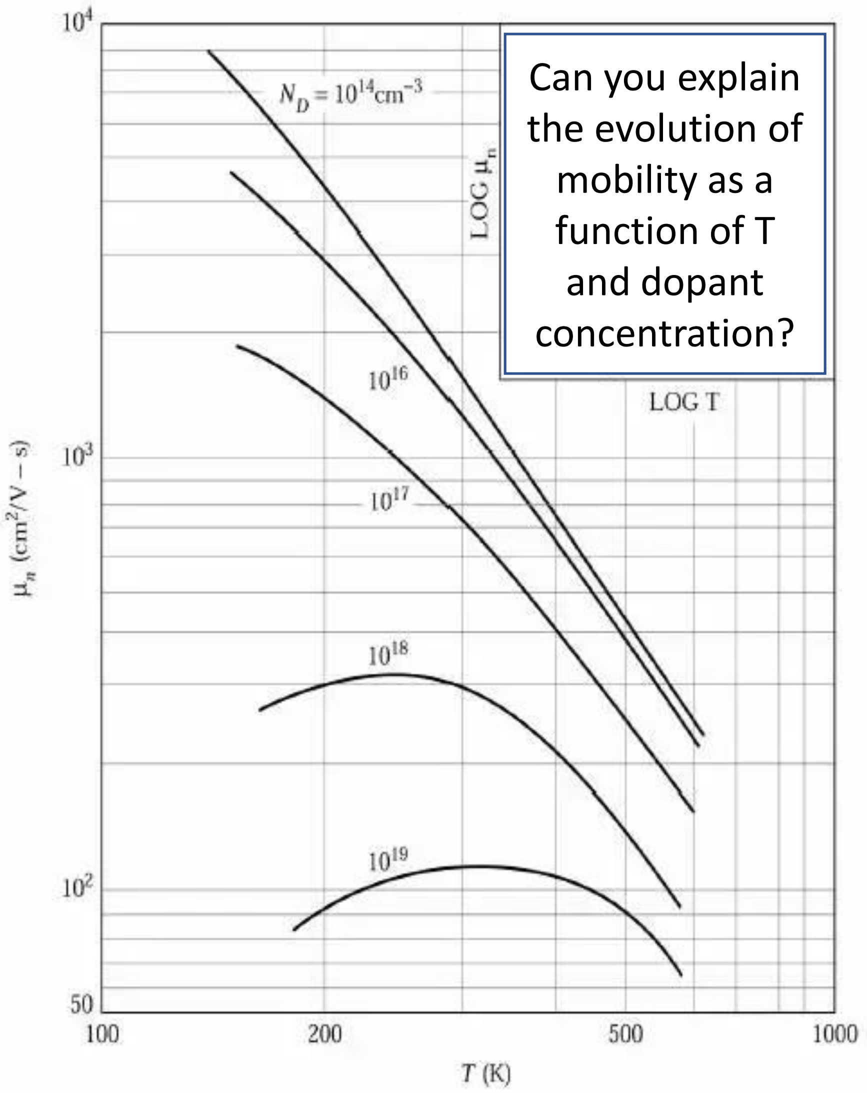


Fig. 8.3 **a** Electron mobility in highly doped silicon. Experimental data (*symbols*) from various sources and modeling with ionized impurity scattering with (*solid line*) and without (*dashed line*) considering impurity clustering. **b** Effective impurity cluster charge Z_D. Adapted from [722]

How would you explain the mobility drop at dopant concentration higher than $10^{20}cm^{-3}$?

Mobility vs T in an ideal doped semiconductor



Can you explain the evolution of mobility as a function of T and dopant concentration?

Crystal defects

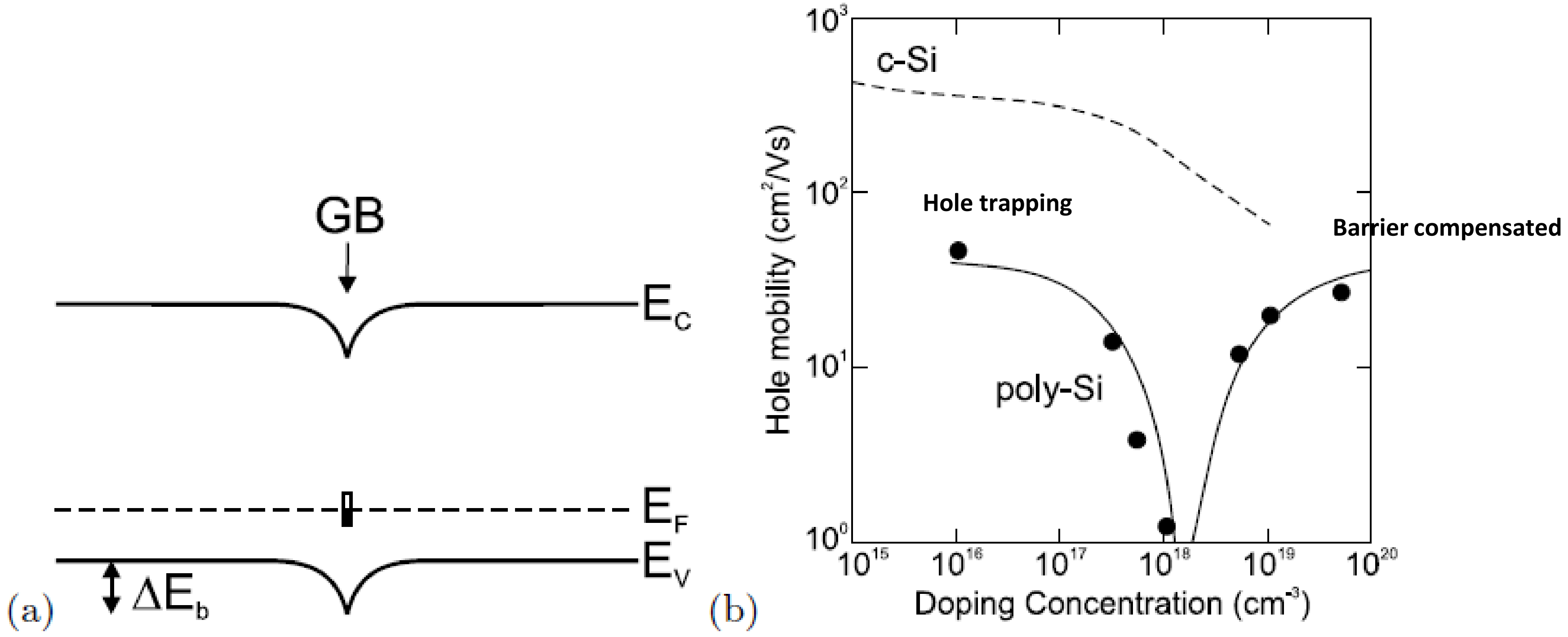


Fig. 8.4 **a** Electronic barrier (ΔE_b) for (hole) transport at a grain boundary (GB). **b** Average hole mobility in poly-silicon, experimental data (*symbols*) and theoretical model (*solid line*). The dependence for monocrystalline silicon is shown for comparison as *dashed line*. Adapted from [730]

Matthiesen's rule

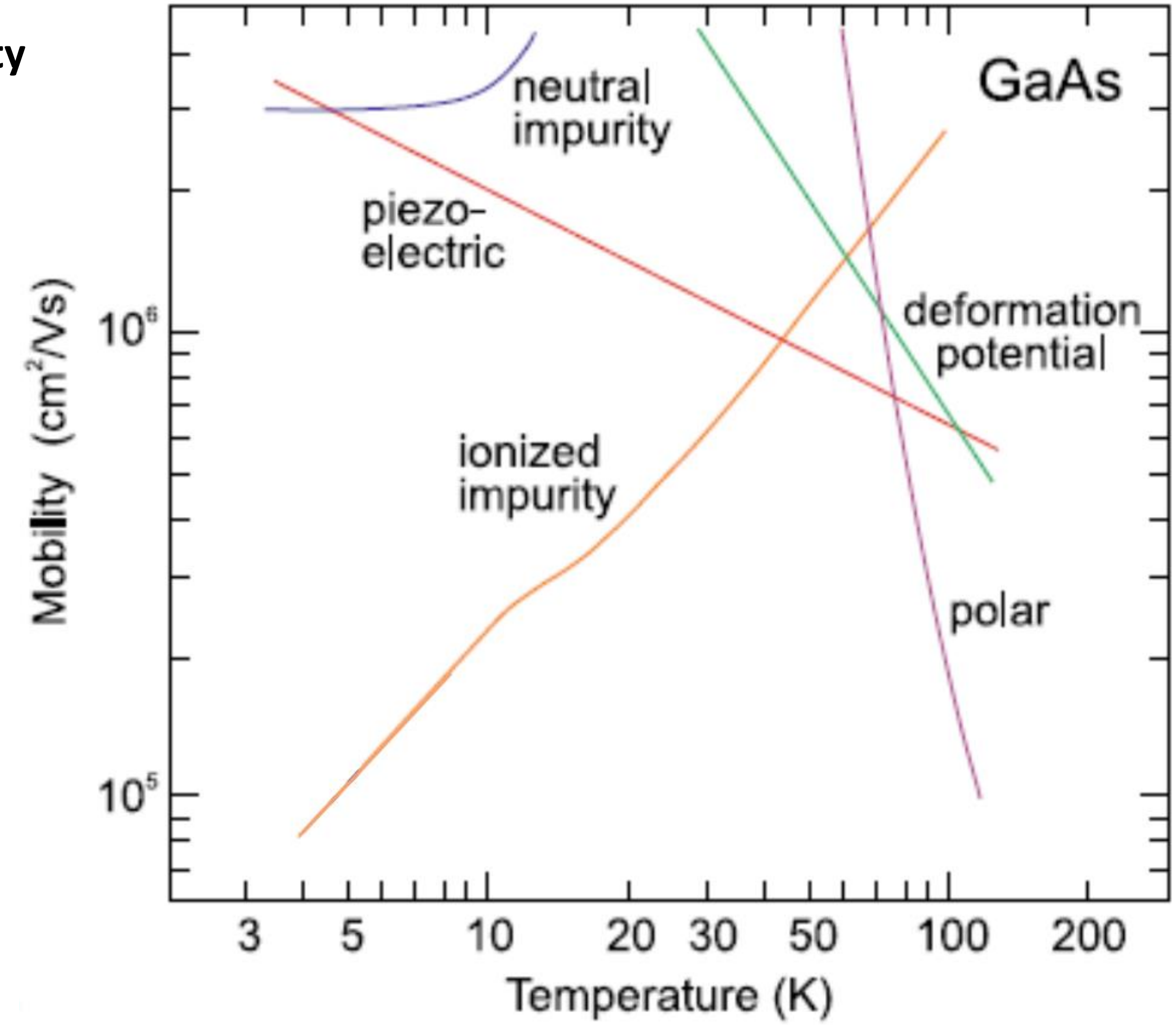
$\frac{1}{\tau}$ → **scattering probability**

$$\frac{1}{\tau^*} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3} + \cdots$$

$$\frac{1}{\tau^*} = \sum_i \frac{1}{\tau_i}$$

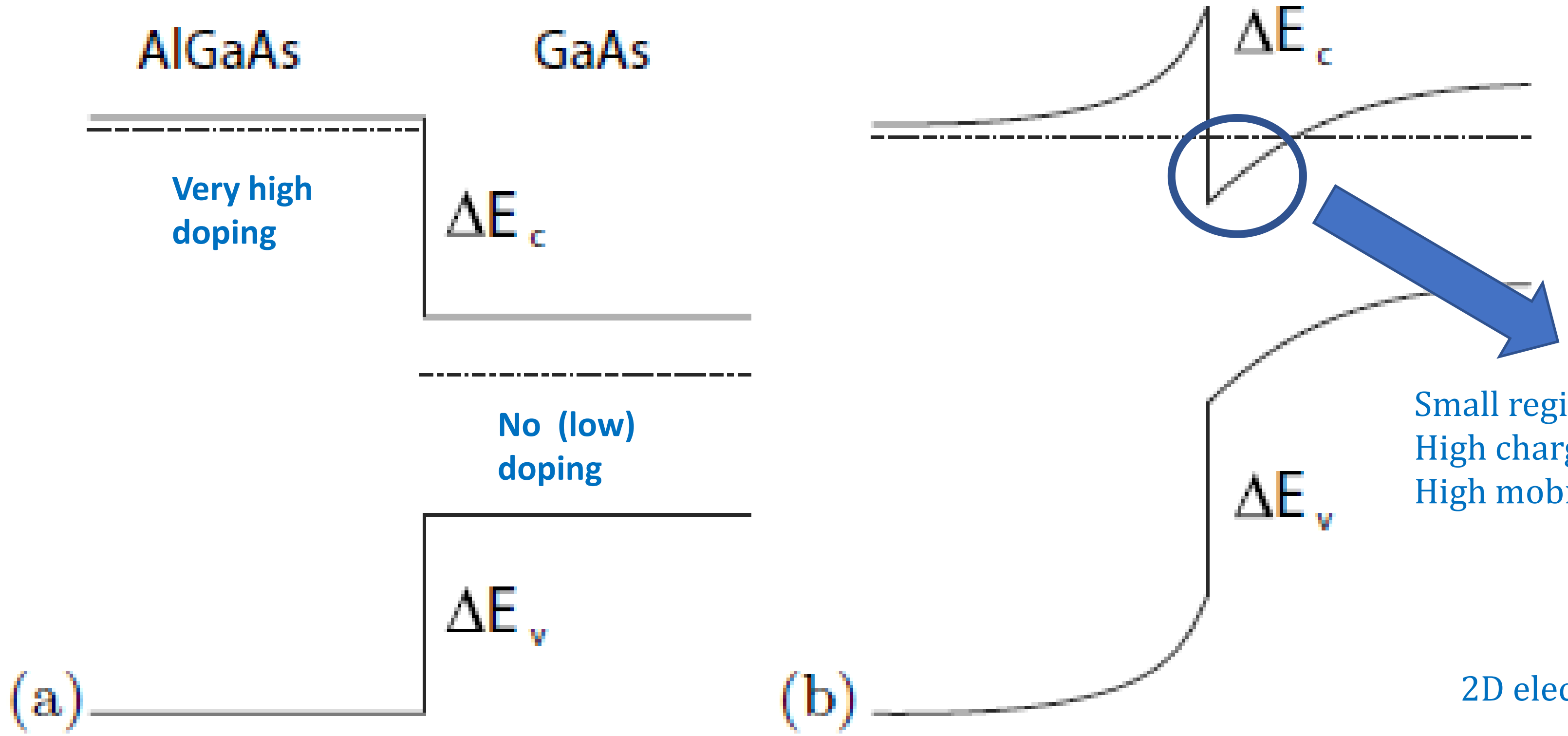
$$(\mu_i = q\,\tau_i / m^*)$$

$$\frac{1}{\mu^*} = \sum_i \frac{1}{\mu_i}$$



Remote doping

$$\mu = -\frac{e\tau}{m^*} \qquad \sigma = -\frac{e^2 n\tau}{m^*}$$



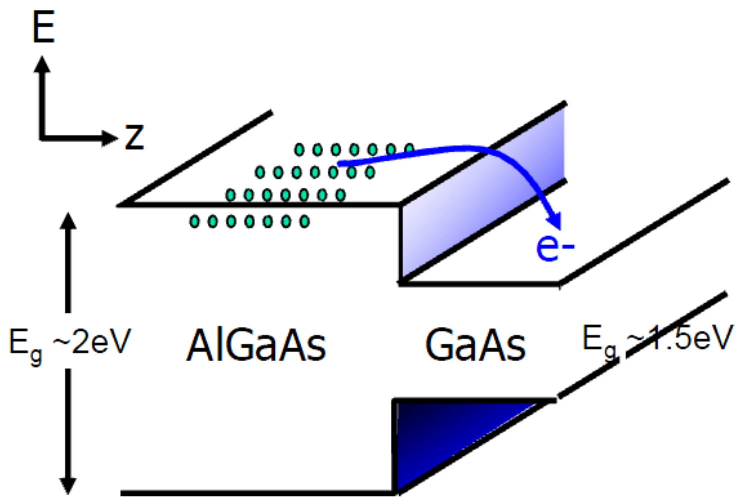
Small region (10 nm) [confinement]
High charge density
High mobility

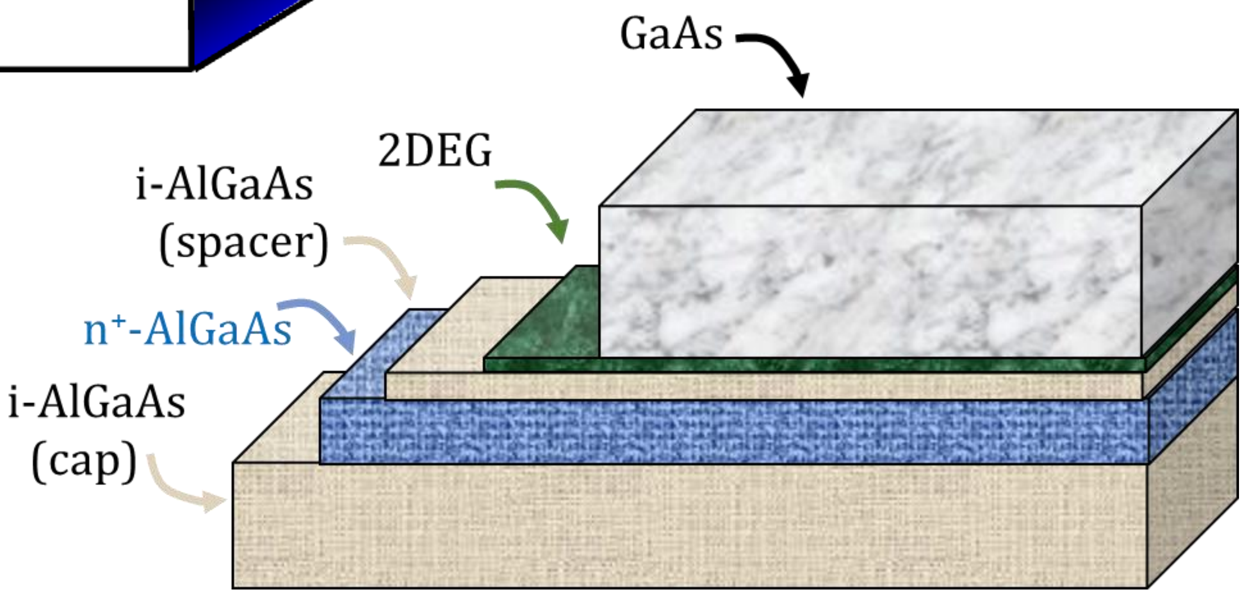
2D electon gas – 2DEG

Principle of
High Mobility Transistor

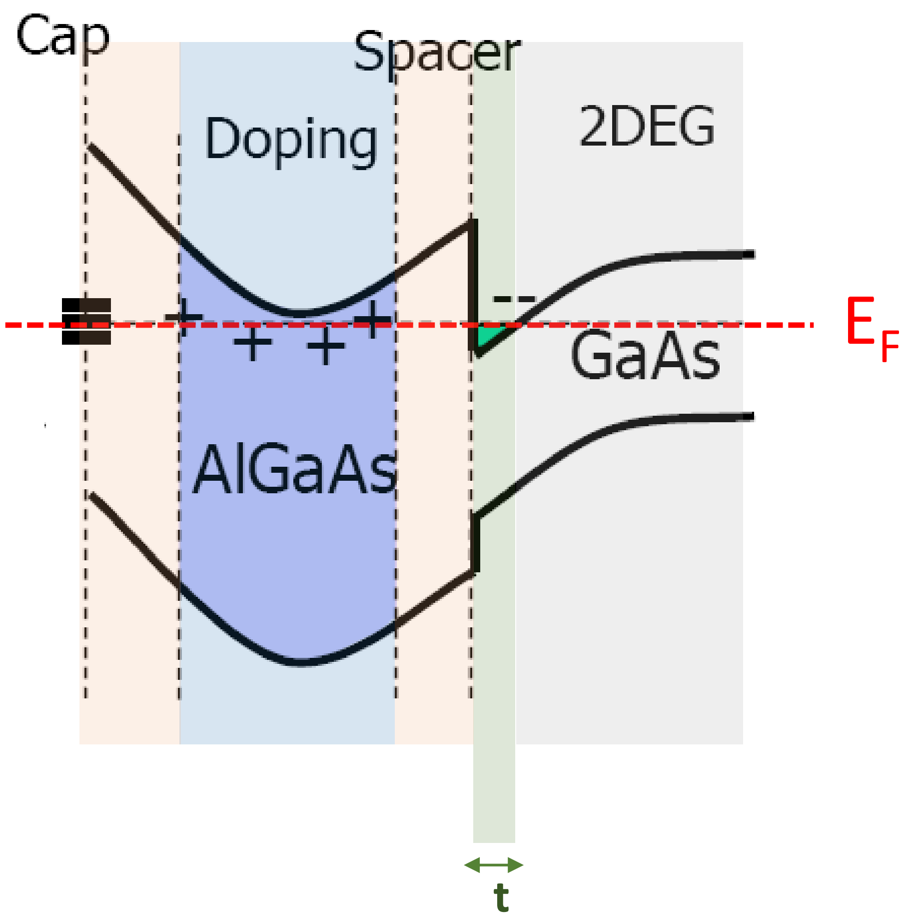
2D Electron Gas (2DEG)

Classical example:
AlGaAs/GaAs heterointerface





Electrons confined in 2D



Engineering a 1D channel in a 2DEG

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Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas

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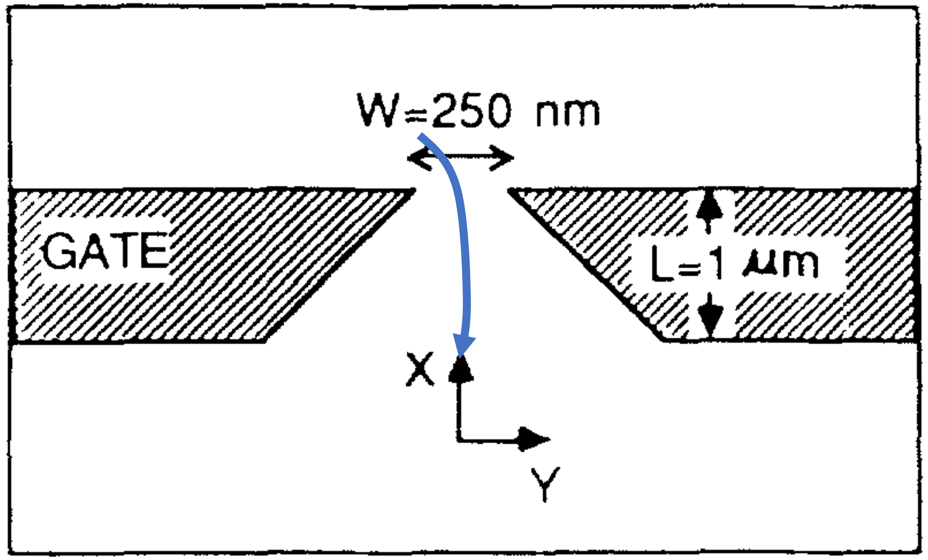
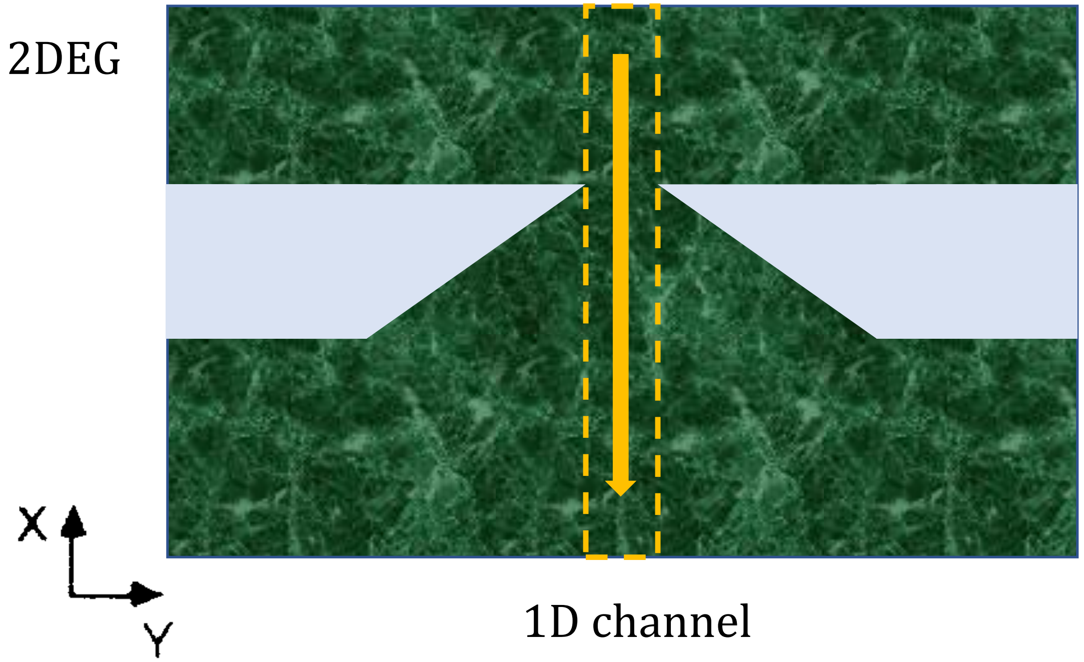
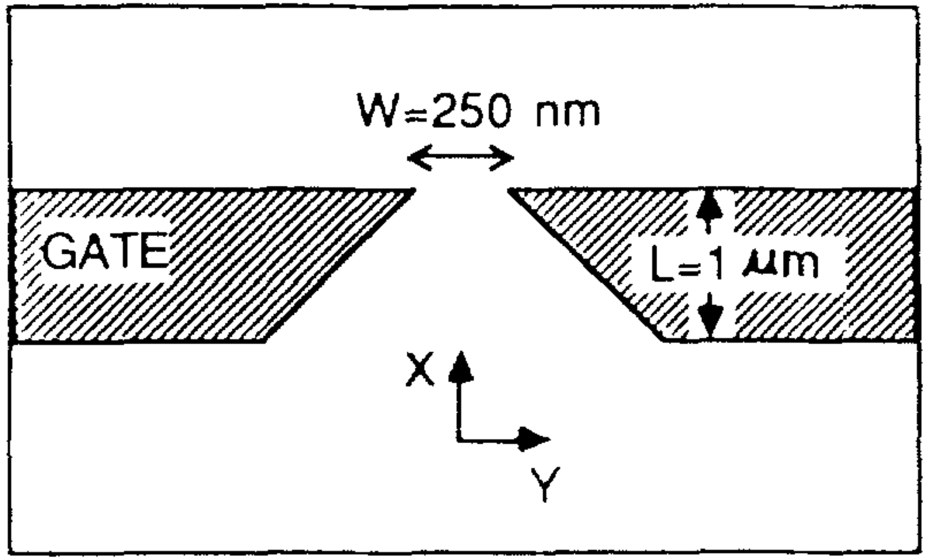
(Received 31 December 1987)



Depletion of carriers beneath the gates
(point contacts)

Engineering a 1D channel in a 2DEG





The depletion of the carrier in the 2DEG induces the formation of a 1D channel.

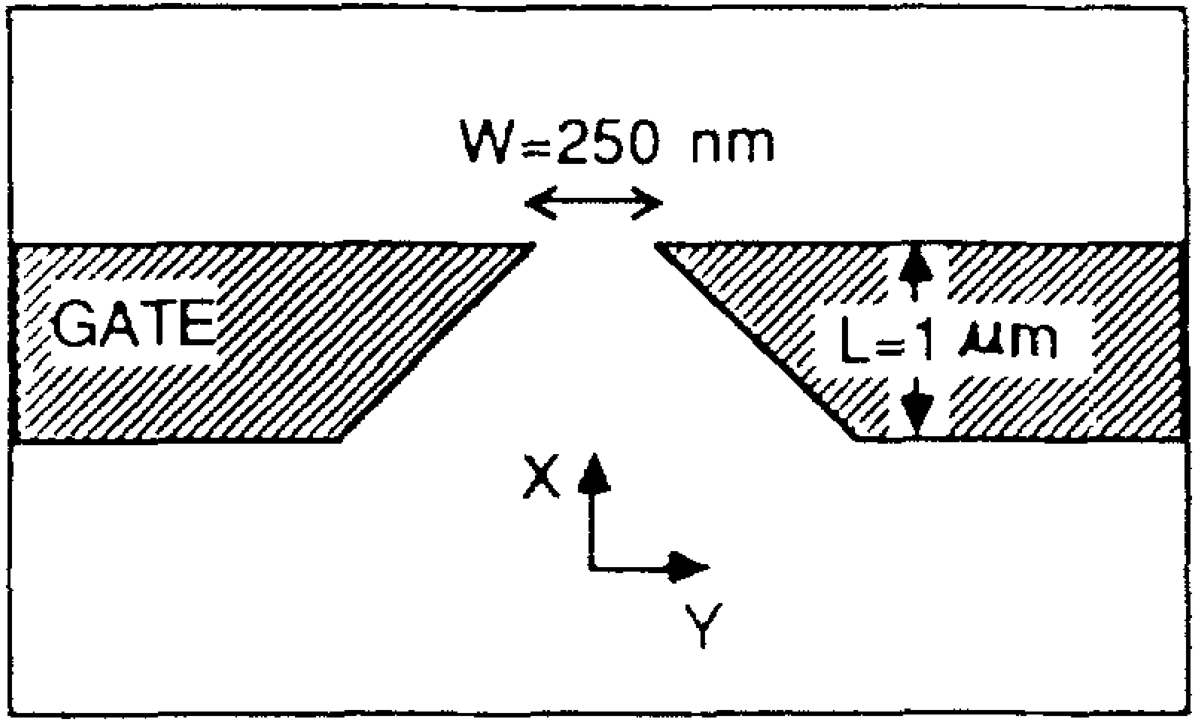
The states flowing in the channel are confined in the y direction with direct consequences on the dispersion relation.

How can we tune the position of the sub-bands?

Tuning the channel properties

Question:

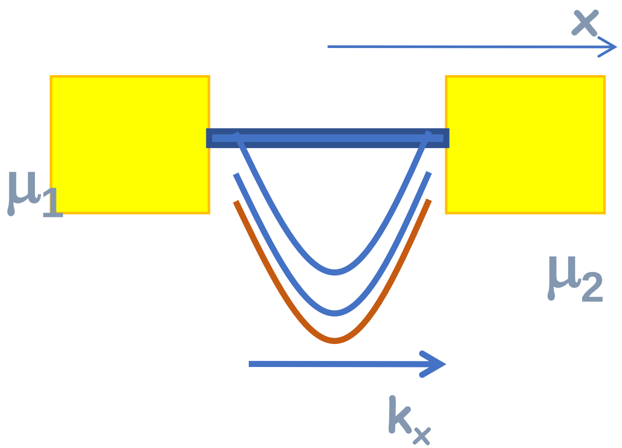
What is the advantage of using a 2DEG to engineer a 1D channel?
How the geometrical parameters affect the physics of the system?



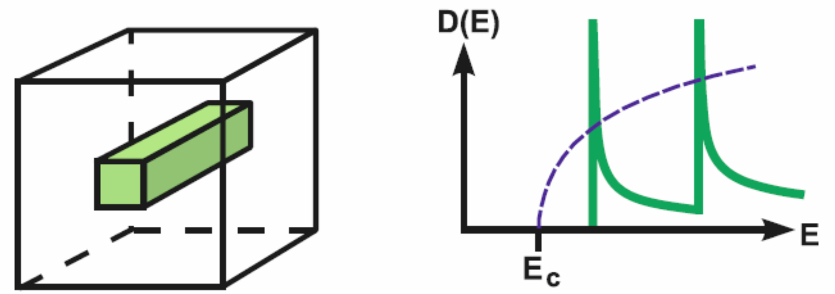
Tuning the channel properties

To be discussed in class

Quantum condactance



Consider a wire with one sub-band occupied connecting two larger reservoirs with a voltage difference V between then.



$D(E) \propto {}^{1}/_{\sqrt{E}}$ $v(E) \propto \sqrt{E}$

$$I = \Delta n \cdot q \cdot v \propto \frac{1}{\sqrt{E}}\sqrt{E}$$ → constant per sub-band

$$J = I = \rho * v_d = n * e * v_d$$

$$n = 2 * D(E) * (\mu_1 - \mu_2)$$

$$V_{bias} = \frac{(\mu_1 - \mu_2)}{e}$$

$$D(E) = \frac{dN}{dk} * \frac{dk}{dE}$$

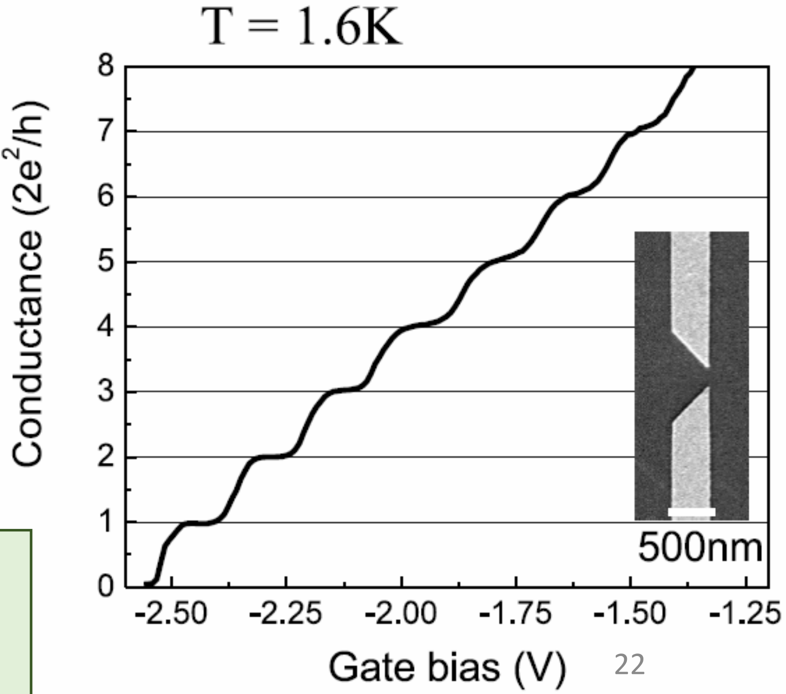
$$v_d = \frac{1}{\hbar} * \frac{dE}{dk}$$

$$G = \frac{I}{V_{bias}} = \frac{2e^2}{h} * D(E) * v_d$$

$$G = \frac{I}{V_{bias}} = \frac{2e^2}{h} * \frac{dN}{dk}$$

Number of sub-bands involved in the conduction (modes)

$$G_0 = \frac{2e^2}{h}$$



LANDAUER FORMULA $$G_N = \frac{2e^2}{h}\sum_{i=1}^{N} T_i$$ T is the transmission of each mode

Imaging Coherent Electron Flow from a Quantum Point Contact

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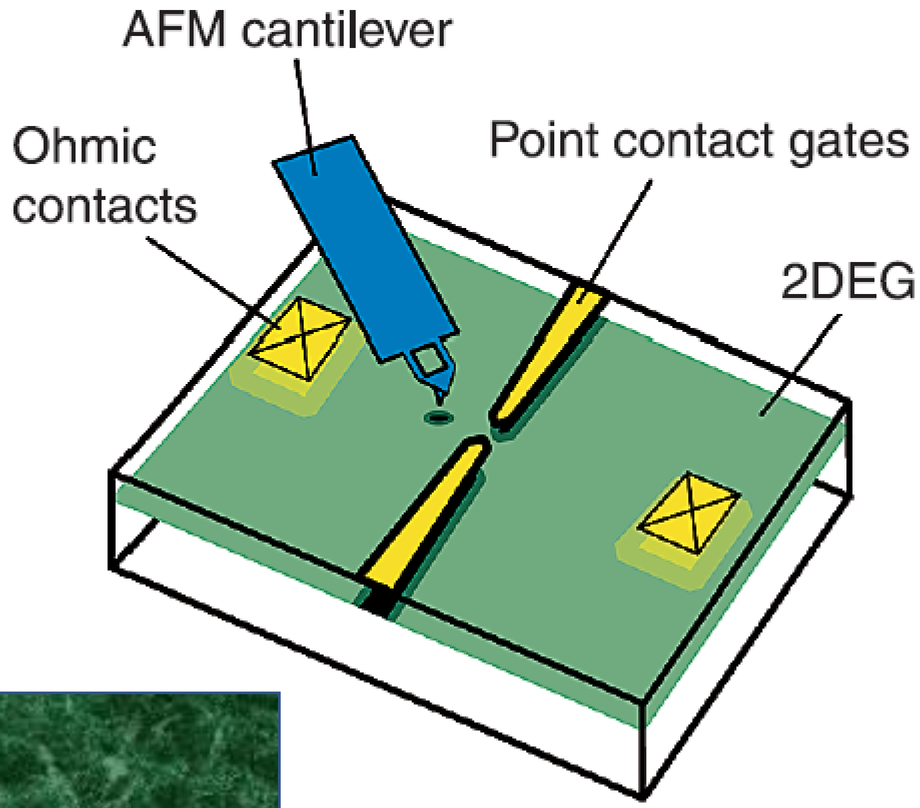
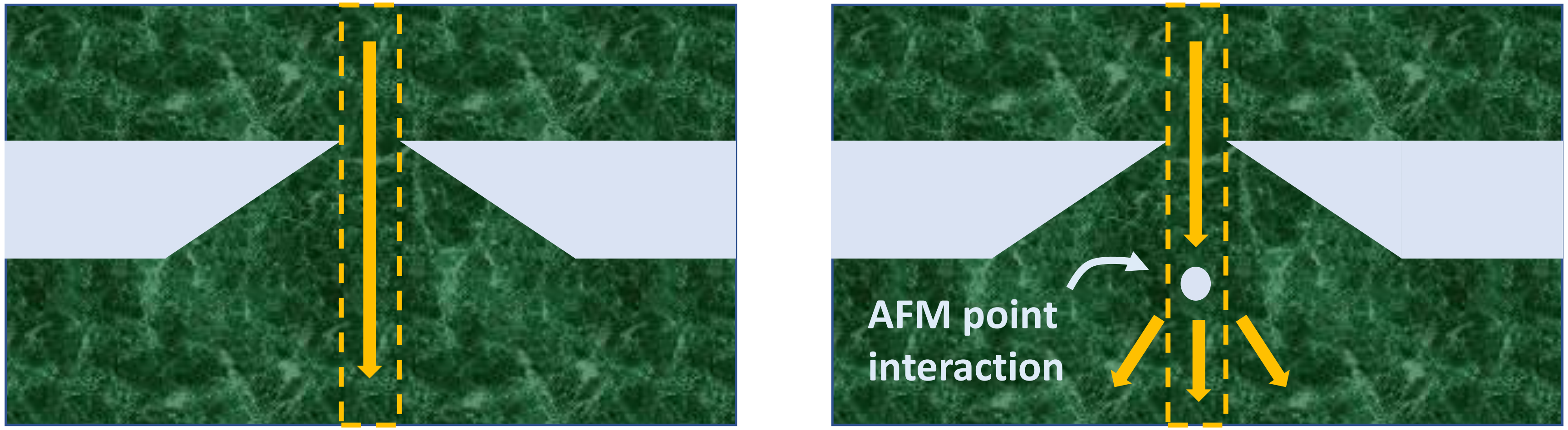
SCIENCE VOL **289** 29 SEPTEMBER 2000

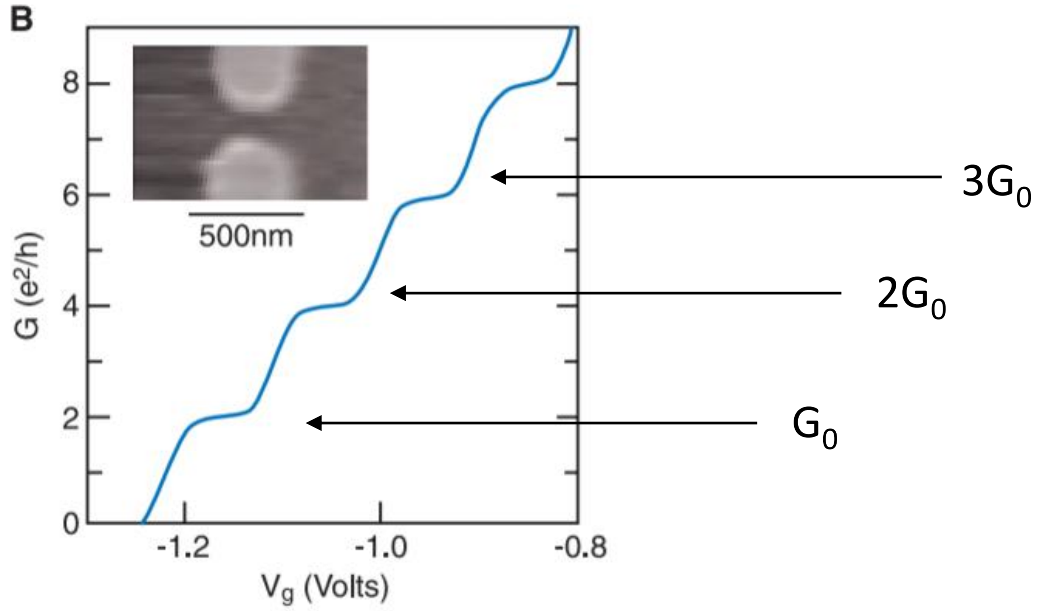


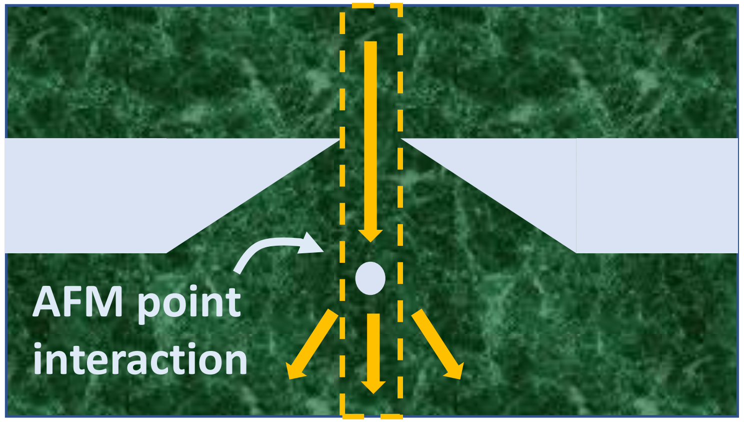
2DEG

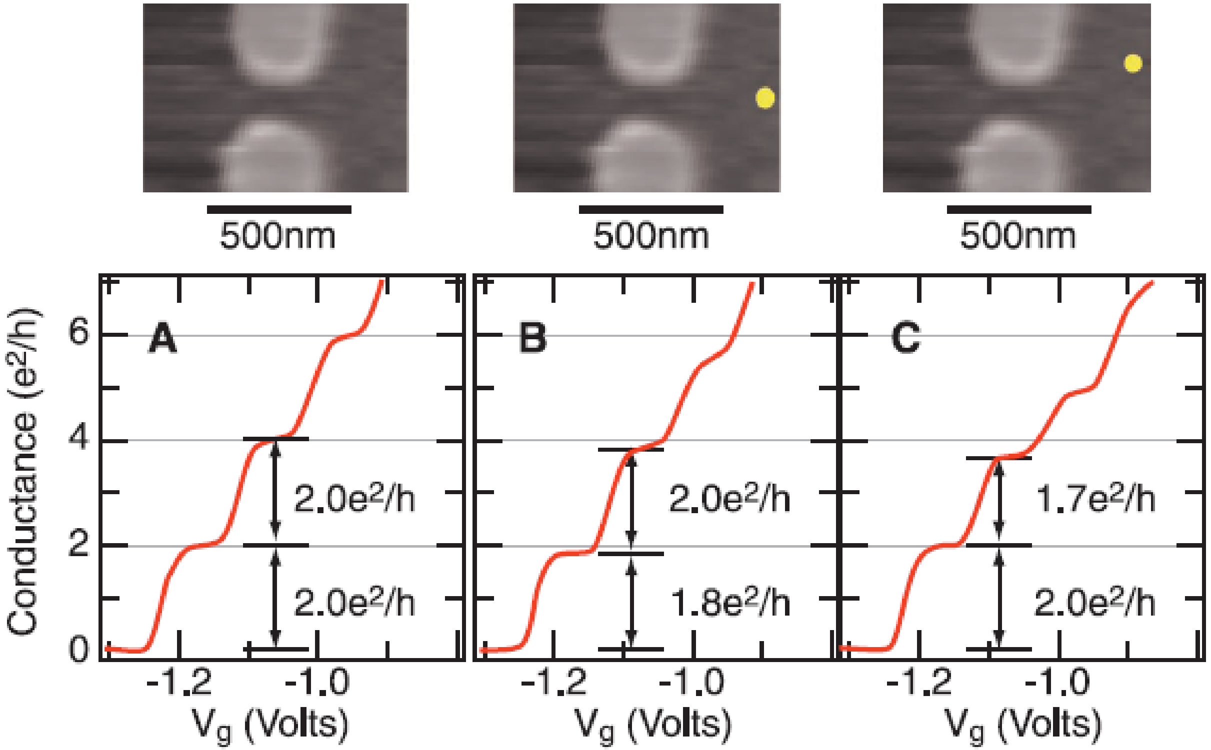


Imaging transmission modes

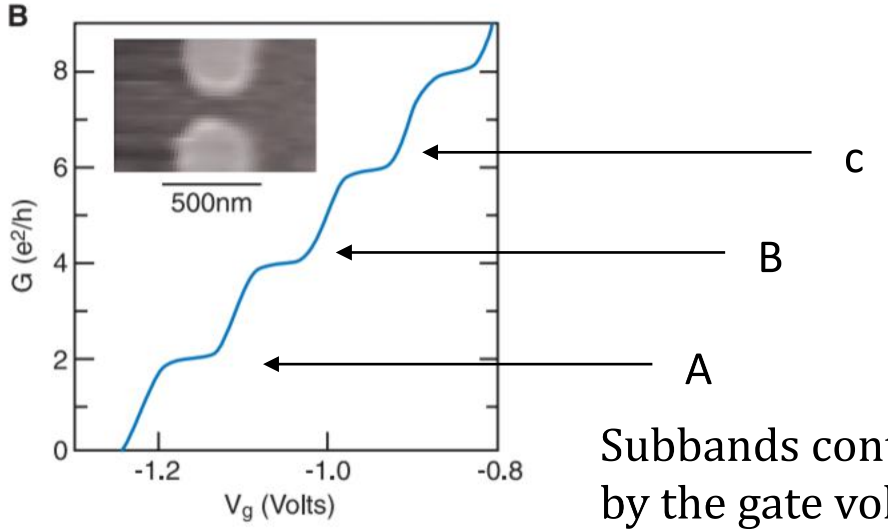
Subbands controlled by the gate voltage



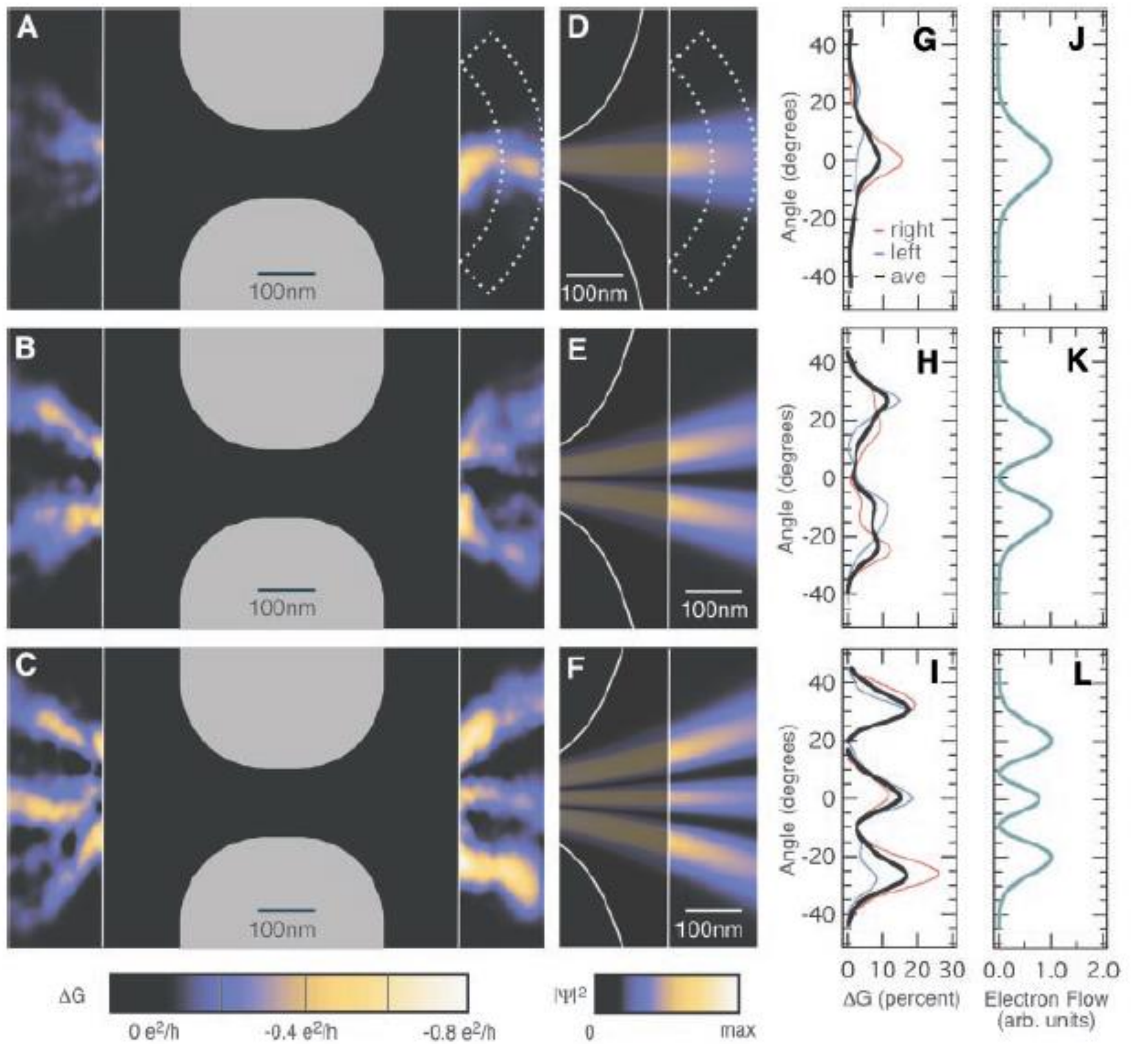




Imaging transmission modes



Subbands controlled by the gate voltage



With increasing channel width:

- The electron flow becomes wider in correspondance of the conductance increase
- Interference patterns are imaged due to constructive/destructive interference of coherent states.