High electron mobility transistors

Carrier drift-velocity and mobility

Carrier drift velocity is related to electric field according to

$$v_{Drift} = \mu \mathcal{E} \quad (1)$$

The validity of this equation is limited to low electric fields. The mobility is a measure of the responsiveness of carrier motion within a semiconductor crystal to an electric field that exerts a force $\boldsymbol{F} = -\boldsymbol{e}\,\mathcal{E}$ on an electron with charge $-\boldsymbol{e}$.

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Material	**Electron mobility** (cm^2 / (Vs))	**Hole mobility** (cm^2 / (Vs))
GaAs	8000	320
GaP	110	70
InP	5600	150
Si	1360	460
Ge	3900	1900
α-SiC	400	50

Table gives values of electron and hole mobilities in semiconductors at room temperature for low doping concentrations.

Data of table shows that electrons are more mobile than holes. This can be generalized for all semiconductors.

Why are electrons generally more mobile than holes? Why is mass of electrons generally lighter than mass of holes?

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Scattering mechanisms

There are different scattering mechanisms such as

- Ionized impurity scattering
- Neutral impurity scattering
- Acoustic phonon scattering
- Optical phonon scattering

Ionized and neutral impurity scattering

Ionized impurity scattering ($\propto 1/\mu_{II}$) increases as the concentration of impurities increases. Coulombic interaction between carrier and charges atom is the cause of ionized impurity scattering. Neutral impurity scattering is weaker than ionized impurity scattering.

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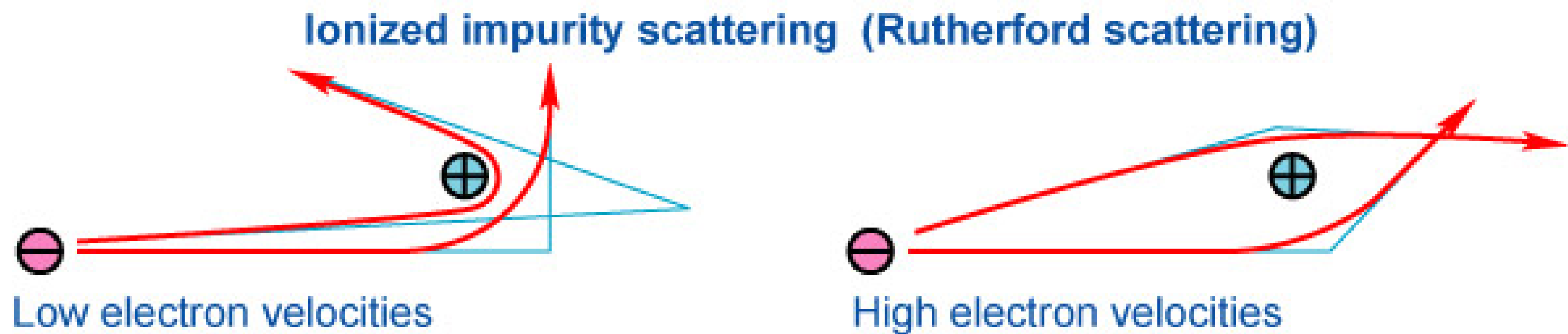
Illustration of possible trajectories:



The analysis of the trajectories of electrons shows that electrons propagate on hyperbolic curves, that is, the trajectories are straight lines sufficiently far away from the impurity.

Give another example as to where in nature hyperbolic curves occur!

The thermal electron velocity can be deduced from the equation:

$$E_{\mathrm{kin}} = \frac{1}{2} m v^2 = \frac{3}{2} k T \qquad (2)$$

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As the thermal velocity of carriers increases with temperature, ionized impurity scattering, becomes less relevant, because the interaction time gets shorter. (***Note***: In highly doped semiconductors, the Fermi velocity rather than the thermal velocity is the relevant velocity.)

A detailed analysis shows that

$$\mu_{\mathrm{II}} \propto T^{3/2} \tag{3}$$

That is, ionized impurity scattering ($\propto 1 / \mu_{\mathrm{II}}$) decreases with increasing temperature.

Naively, one would assume that ionized impurity scattering is directly proportional to the number of ionized impurities, *i. e.*

$$\mu_{\mathrm{II}} \propto N_{\mathrm{II}}^{-1}$$

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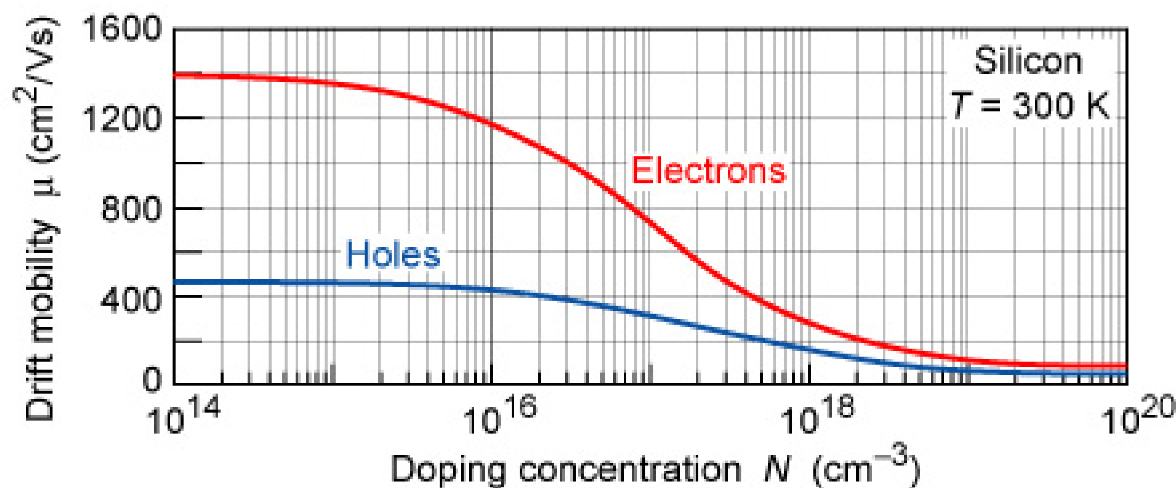
However, the dependence is weaker due to the effect of screening. One finds that

$$\mu_{II} \propto \left(N_{II}^{-1}\right)^{\alpha} \qquad \text{where } \alpha < 1 \qquad (4)$$

At a given temperature, the mobility decreases as the doping concentration increases. This can be verified from the following graph which shows experimental electron and hole mobilities in silicon at room temperature:



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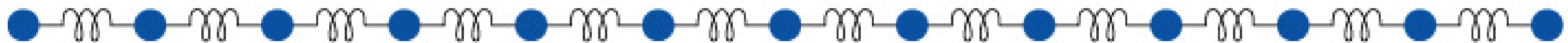
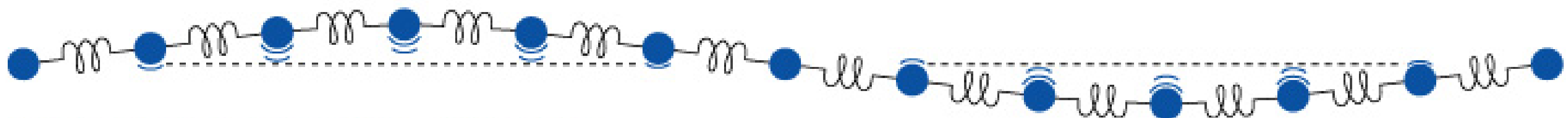
Phonons

Phonons are lattice vibrations. There are 4 types of phonons in a one-dimensional (1D) chain of atoms, namely the transverse acoustical type (**TA**), the longitudinal acoustical type (**LA**), transverse optical type (**TO**), the longitudinal optical type (**LO**).

1D chain of atoms connected by springs



1D chain of atoms with TA vibration



1D chain of atoms with LA vibration

1D chain of atoms with TO vibration

1D chain of atoms with LO vibration

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Exercises:

- Compare the wavelengths of acoustic and optical phonons!
- What is the direction of motion of adjacent atoms for TA, LA, TO, and LO phonons?
- Which type, acoustical or optical type of oscillations, do you suppose, has greater energy?
- What is the phase velocity of TA and LA oscillations?
- Is energy of lattice vibrations quantized?
- How are phonon frequency and energy related?

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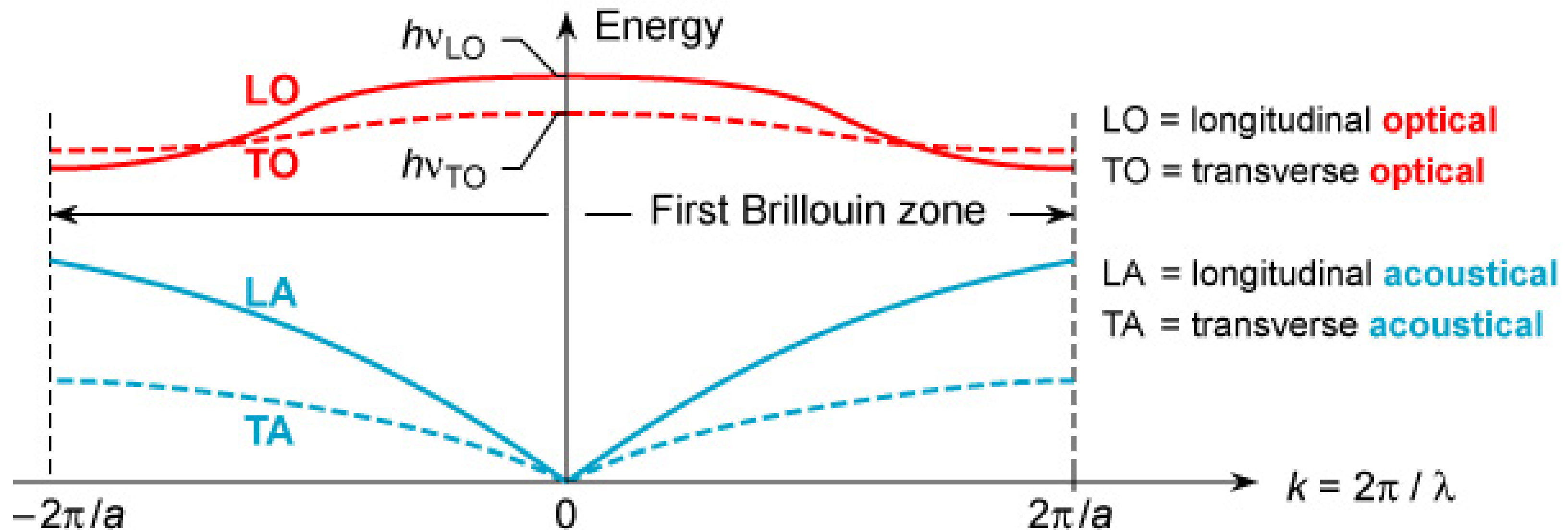
Schematic phonon dispersion in 1D lattice



Acoustic phonon scattering

Acoustic scattering is due to the emission or absorption of phonons. *i. e.* quantized lattice-vibrational waves. Acoustic phonon scattering ($\propto 1/\mu_{AC}$) increases with temperature. There are more phonons around at high temperatures compared with low temperatures.

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A detailed analysis shows that

$$\mu_{AC} \propto T^{-3/2} \quad (5)$$

At any doping concentration, the mobility decreases as temperature increases.

At low doping concentrations, the mobility is mostly affected by acoustic phonon scattering.

At high doping concentrations, the mobility is affected by both impurity and phonon scattering.

Optical phonon scattering

Optical phonon scattering ($\propto \mu_{OP}$) occurs when carriers have substantial kinetic energy. Optical phonons have an energy of *e. g.* $h\nu_{OP}$ = 36 meV (for GaAs). To emit an optical phonon, the carrier must have an energy greater or equal to $h\nu_{OP}$.

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Matthiesen's rule

$$\frac{1}{\mu} = \frac{1}{\mu_{II}} + \frac{1}{\mu_{AC}} + \frac{1}{\mu_{OP}} \quad (6)$$

Inverse mobilities can be considered the hindrances. Matthiesen's rule implicates that hindrances add up.

Generalization of Matthiesen's rule:

$$\frac{1}{\mu} = \sum_i \frac{1}{\mu_i} \quad (7)$$

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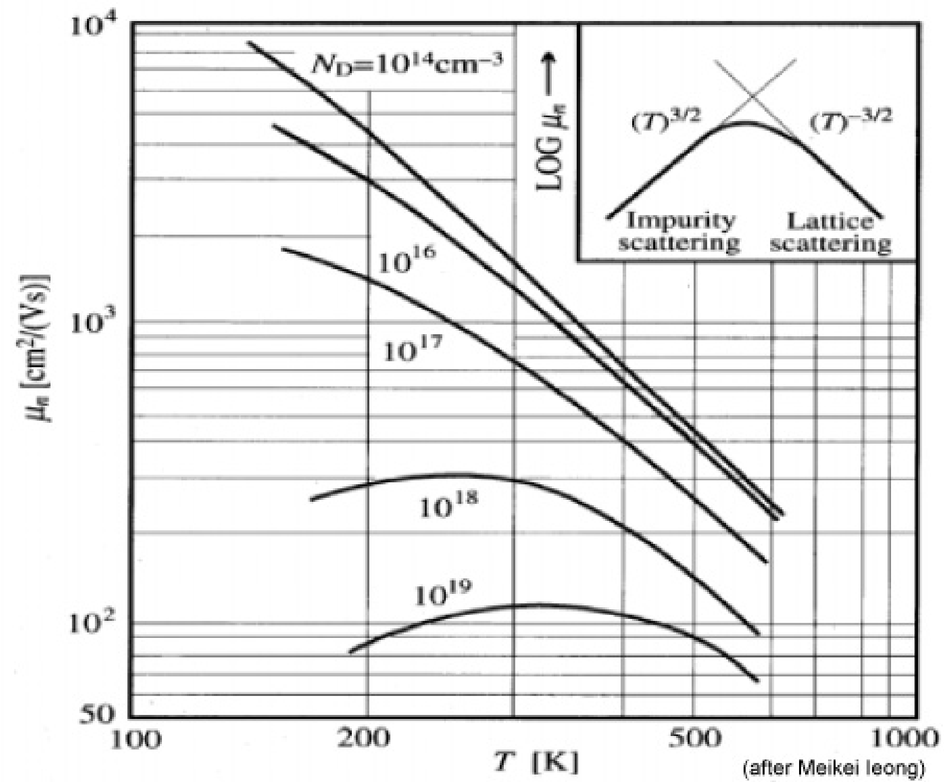
Mobility versus temperature for different doping concentrations:



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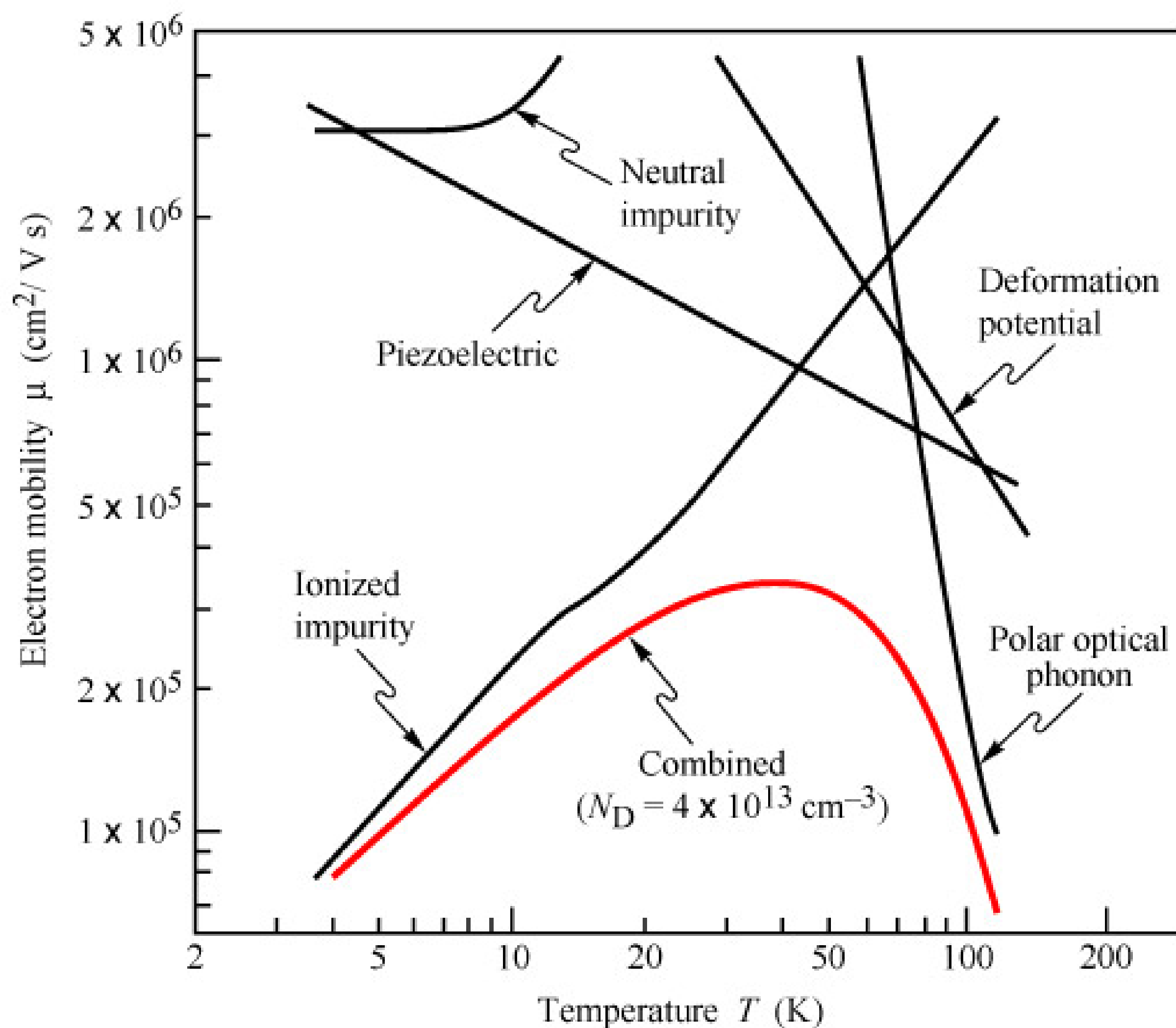
Summary of scattering mechanisms:



Calculated electron mobilities due to different scattering mechanisms and combined mobility inferred from Matthiessen's rule in high purity GaAs (N_D = 4 x 10^{13} cm^{-3}) as a function of temperature (after Wolfe et al., 1970).

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Summary of scattering mechanisms:

(1) Scattering by phonons occurs at all finite lattice and electron temperatures. Scattering by optical phonons dominates the mobility at temperatures > 100 K.

(2) Alloy scattering due to random distribution of Al and Ga in the alloy $Al_xGa_{1-x}As$ is a scattering mechanism in all alloy semiconductors. It can be a significant.

(3) Neutral and ionized impurity scattering. The scattering by neutral impurities is much weaker than the scattering by ionized impurity atoms due to the lack of Coulomb charge.

(4) Deformation potential and piezoelectric scattering are minor scattering mechanisms (see illustration).

General note:

Ionized impurity scattering is elastic scattering (no energy loss).
Phonon scattering is inelastic (energy loss).

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Phenomenological mobility modeling

The experimental mobility versus doping concentration can be fitted with:

$$\mu_n = \mu_{HC} + \frac{\mu_{LC} - \mu_{HC}}{1 + \left(N_D / N_{1/2}\right)^{2/3}} \quad (8)$$

where μ_{LC} is the low-concentration mobility, μ_{HC} is the low-concentration mobility, N_D is the n-type doping concentration, and $N_{1/2}$ is the concentration at which the mobility is reduced by approximately a factor of two as compared to the low-concentration mobility.

At low concentrations, the denominator has unit value and the mobility is given by μ_{LC}. At high concentrations, the denominator is approximately $(N_D / N_{1/2})^{2/3}$ so that the mobility decreases by a factor of $(10)^{2/3} \approx 4.6$ per order of magnitude of doping concentration. At very high concentrations, the mobility approaches μ_{HC}.

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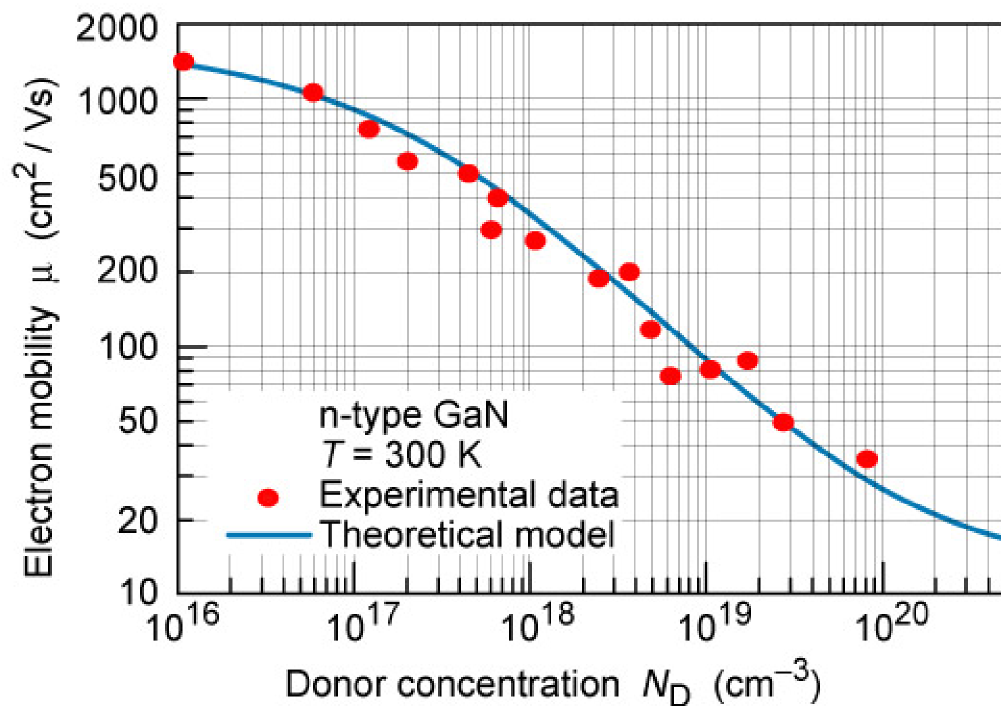
Parameters for n-type GaN:

μ_{LC} = 1800 cm^2 / (Vs), μ_{HC} = 10 cm^2 / (Vs), and $N_{1/2}$ = 1.0 × 10^{17} cm^{-3}



Theoretical model:

$\mu = \mu_{HC} + (\mu_{LC} - \mu_{HC}) / [1 + (N_D / N_{1/2})^{2/3}]$

where

μ_{LC} = 1800 cm^2 / Vs

μ_{HC} = 10 cm^2 / Vs

$N_{1/2}$ = 1 × 10^{17} cm^{-3}

Parameters for p-type GaN:

μ_{LC} ≈ 40 cm^2 / (Vs), μ_{HC} ≈ 1 cm^2 / (Vs), and $N_{1/2}$ ≈ 1.0 × 10^{17} cm^{-3}

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More sophisticated mobility versus doping concentration formulas, including the temperature dependence, can be found, for example, in the "Atlas User's Manual", a device simulation software manual (Silvaco Corporation, Version 1.5.0, 1997).

For the modeling of mobility, see also J. Piprek "Semiconductor Optoelectronic Devices: Introduction to Physics and Simulation" 352 pages (Academic Press, San Diego, 2003) ISBN: 0125571909

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Saturation velocity

At high electric fields, the carrier mobility becomes irrelevant and carriers drift with the drift saturation velocity. The saturation velocity is mostly determined by optical phonon energy. Semiconductors with a large LO phonon energy have a high saturation velocity.

The saturation velocity of all semiconductors is of the order of 10^7 cm/s.

Drift saturation velocities of semiconductors.

Material	**Diamond**	**Si**	**GaAs**	**SiC**
Saturation velocity (10^7 cm/s)	2.7	1.0	2.0	2.7
Breakdown field (10^5 V/cm)	100	3	4	30

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Modulation doping

We have learned that mobilities decrease as the doping concentration increases.

Question:

Is there a way to avoid the mobility penalty at high doping concentrations?

Answer: Yes there is a way! This is called modulation doping.

Modulation doping is a concept that creates a two-dimensional electron gas with high carrier mobility.

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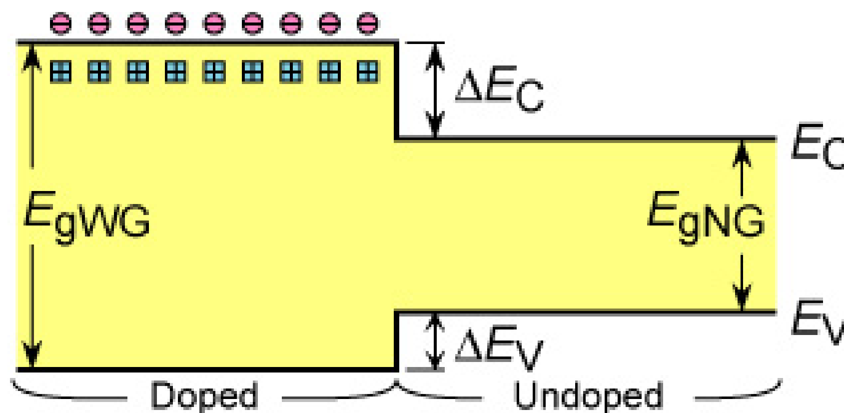
Basic modulation-doped structure

The basic structure consists of a doped wide-bandgap semiconductor adjoining a narrow-bandgap semiconductor.



Conduction band discontinuity: ΔE_C

Valence band discontinuity: ΔE_V

E_g of **W**ide-**G**ap material: E_{gWG}

E_g of **N**arrow-**G**ap material: E_{gNG}

Discontinuity ratio: $\Delta E_C / \Delta E_V$

$$\Delta E_C + \Delta E_V = \Delta E_g = E_{gWG} - E_{gNG} \tag{9}$$

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The ratio of $\Delta E_C / \Delta E_V$ depends of the material system. The $Al_xGa_{1-x}As$ / GaAs material system has a ratio of about

$$\Delta E_C / \Delta E_g = 2/3 \tag{10}$$

The discontinuity in the AlGaAs / GaAs system is usually higher in the conduction band due to the **common-anion rule**.

Question: What is the common anion rule?

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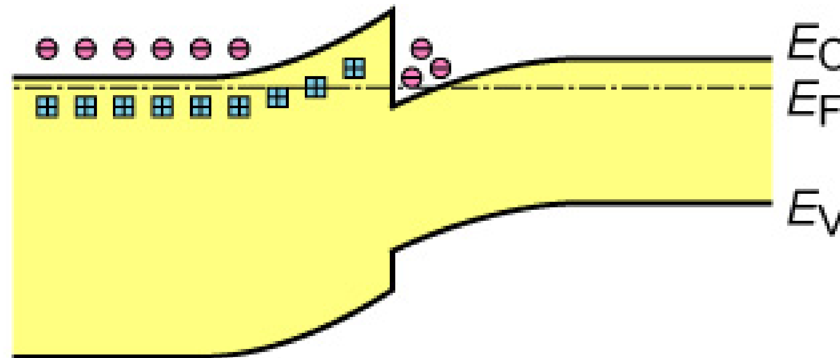
Carriers originating from their parent dopants in the wide-gap material transfer to the narrow-gap material due to the availability of states at lower energy.



Band bending results as a consequence of the charge transfer.

Free electron gas is created in the narrow-gap material at the boundary between the two semiconductors.

Electrons are spatially separated from donors thereby reducing ionized-impurity scattering.

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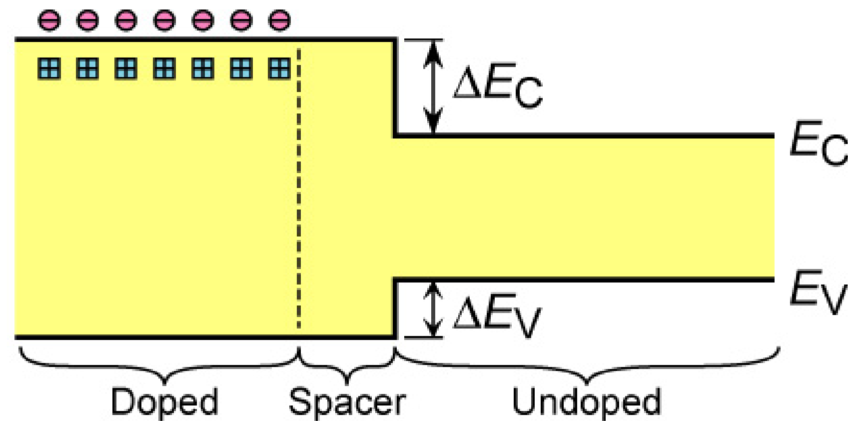
Separation between electrons and donors can be further enhanced with a spacer layer.



Record mobilities have been obtained in modulation-doped heterostructures with a spacer layer.

Typical mobilities in modulation-doped heterostructures: 7 000 cm^2/Vs

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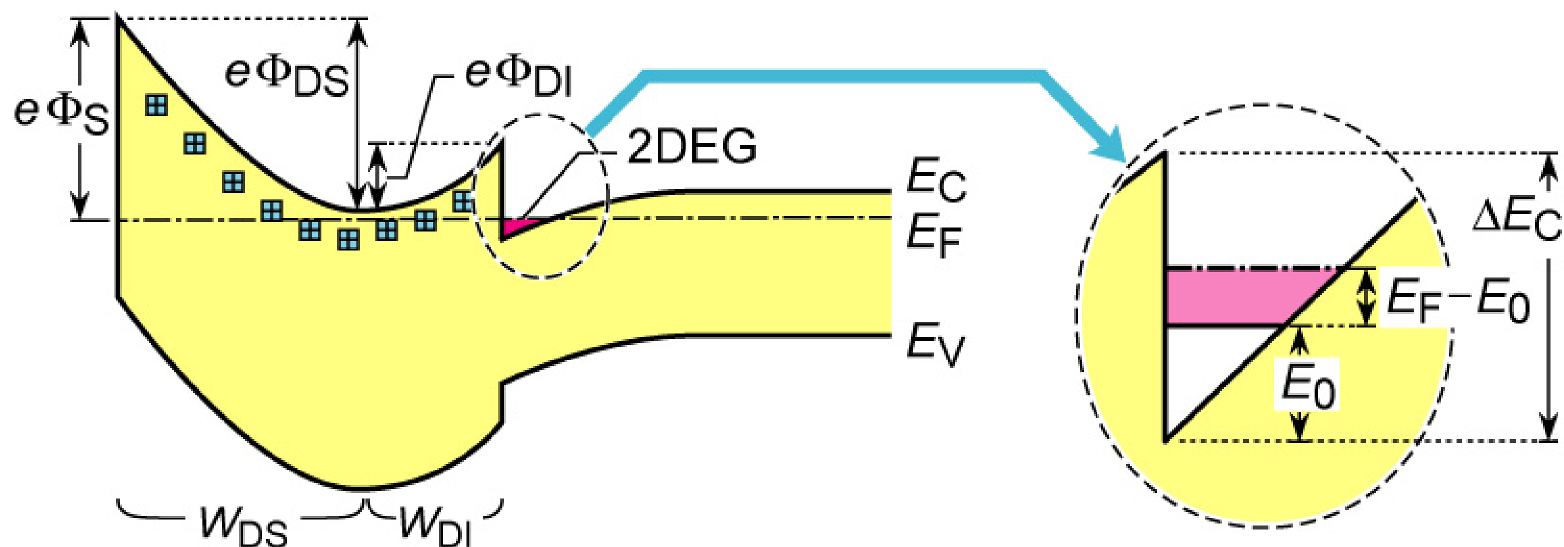
Quantitative analysis of electron gas concentration:



Two-dimensional electron gas (2DEG) concentration:

$$n_{\mathrm{2DEG}} = N_{\mathrm{D}} W_{\mathrm{DI}} \tag{11}$$

Recall Poisson's and Gauss' equation:

$$\frac{\mathrm{d}^2\Phi}{\mathrm{d}x^2} = -\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}x} = -\frac{\rho}{\varepsilon}$$

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Electric field in GaAs at interface follows from Gauss' equation:

$$\mathcal{E} = \frac{e N_{\mathrm{D}} W_{\mathrm{DI}}}{\varepsilon_{\mathrm{GaAs}}} = \frac{e n_{\mathrm{2DEG}}}{\varepsilon_{\mathrm{GaAs}}} \tag{12}$$

Quantized energy of 2DEG ground state ($n = 0$):

$$E_0 = \left(\frac{9\pi}{8}\right)^{2/3} \left(\frac{e^2 \hbar^2 \mathcal{E}^2}{2 m^*}\right)^{1/3} \tag{13}$$

2D density of states:

$$\rho_{\mathrm{DOS}}^{\mathrm{2D}} = \frac{m^*}{\pi \hbar^2} \tag{14}$$

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Degeneracy energy of electron gas:

$$E_F - E_0 \;=\; n_{2DEG} \big/ \rho^{2D}_{DOS} \;=\; n_{2DEG} \Big/ \left(\frac{m^*}{\pi \hbar^2} \right) \qquad (15)$$

Surface depletion width:

$$W_{DS} \;=\; \sqrt{\frac{2\, \varepsilon_{AlGaAs}}{e\, N_D}\; \Phi_{DS}} \;\approx\; \sqrt{\frac{2\, \varepsilon_{AlGaAs}}{e\, N_D}\; \Phi_S} \qquad (16)$$

Interface depletion width:

$$W_{DI} \;=\; \sqrt{\frac{2\, \varepsilon_{AlGaAs}}{e\, N_D}\; \Phi_{DI}} \qquad (17)$$

Condition of constancy of Fermi level at interface is given by:

$$\left(E_C - E_F\right)\Big|_{AlGaAs} + e\Phi_{DI} - \Delta E_C + E_0 + (E_F - E_0) \;=\; 0 \qquad (18)$$

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Neglecting the difference between the Fermi level and the minimum of the CB in the AlGaAs, the equation can be simplified to:

$$e\Phi_{DI} - \Delta E_C + E_0 + (E_F - E_0) = 0 \tag{19}$$

Using the equations above, we express all energies and potentials in Eq. (19) as a function of n_{2DEG}:

$$\Phi_{DI} = \frac{W_{DI}{}^2 \, e N_D}{2\varepsilon_{AlGaAs}} = \frac{e\,(W_{DI} N_D)^2}{2 N_D \, \varepsilon_{AlGaAs}} = \frac{e\, n_{2DEG}{}^2}{2 N_D \, \varepsilon_{AlGaAs}} \tag{20}$$

$$\Delta E_C = (2/3)\, \Delta E_g \tag{21}$$

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$$E_0 = \left(\frac{9\,\pi}{8} \right)^{2/3} \left(\frac{e^2\, \hbar^2 \left(\frac{e\, n_{2DEG}}{\varepsilon_{GaAs}} \right)^2}{2\, m^*} \right)^{1/3} \quad (22)$$

$$E_F - E_0 = n_{2DEG} \Big/ \rho_{DOS}^{2D} = n_{2DEG} \Big/ \left(\frac{m^*}{\pi \hbar^2} \right) \quad (23)$$

Inserting Eqs. (20) – (23) into Eq. (19), we obtain one equation with the unknown n_{2DEG}. We can solve this equation by numerically finding the solution (there is no analytic solution to the equation).

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It is useful to re-write Eq. (19) as

$$\Delta E_C = E_0 + (E_F - E_0) + e\,\Phi_{DI} \tag{24}$$

This equation allows us to deduce the “driving forces” of the 2DEG density.

Exercise:

Describe which parameters need to be maximized or minimized in order to obtain a high concentration of the 2DEG density.

What is the role of ΔE_C?
What is the role of N_D?
What is the role of m^*?
How would a spacer layer affect the 2DEG density, n_{2DEG}?

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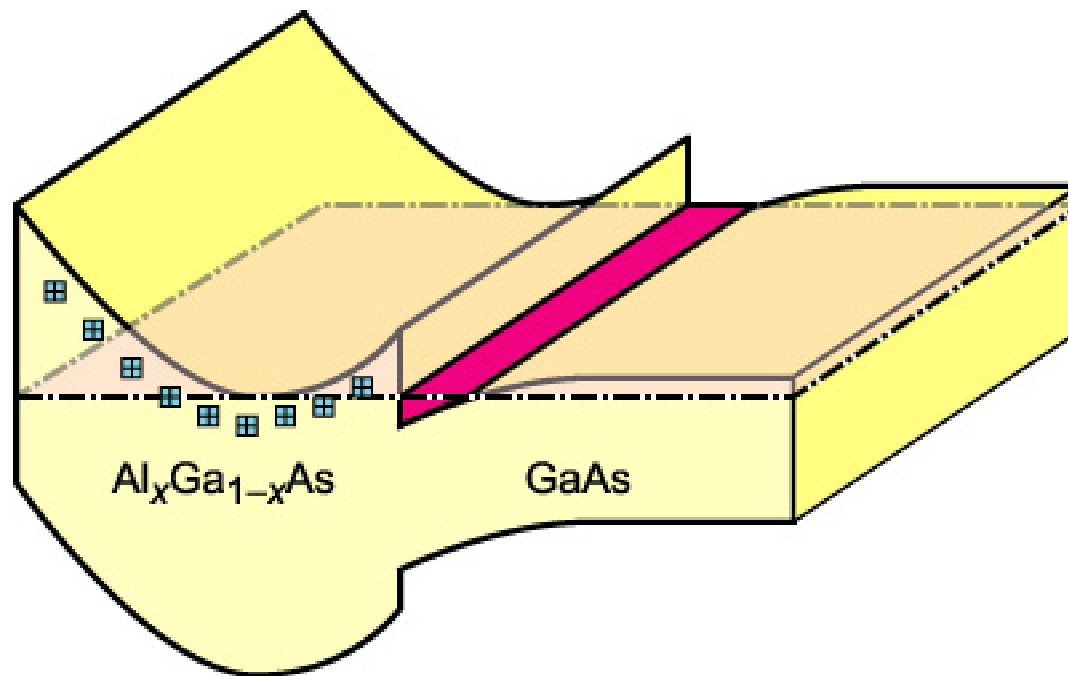
Three-dimensional illustration of a modulation-doped structure:



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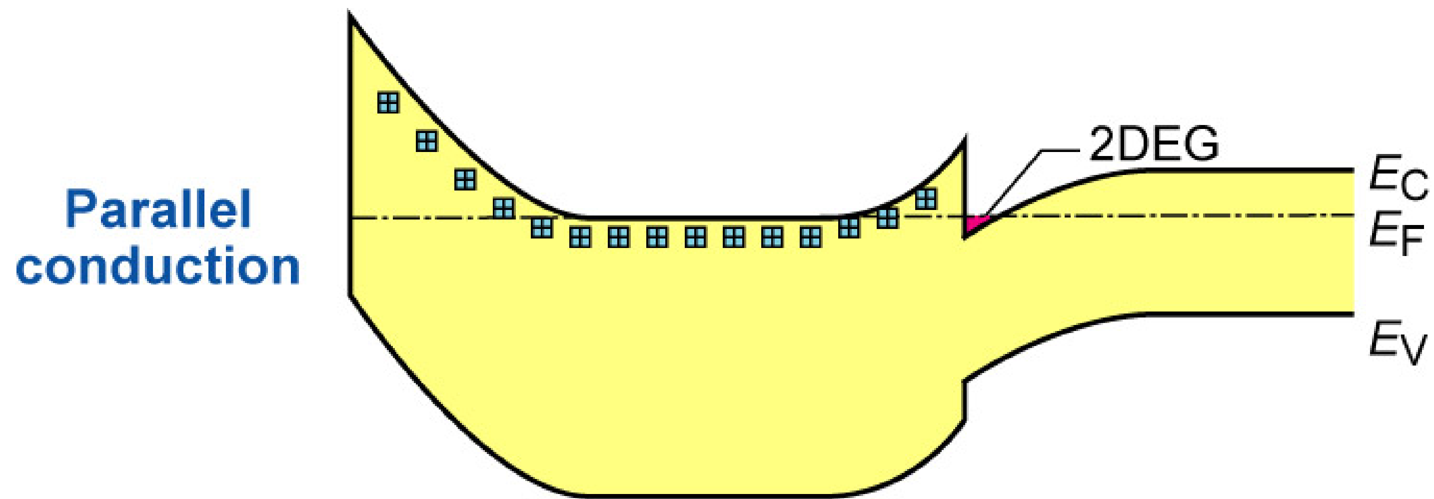
Parallel conduction:



- Parallel conduction in the AlGaAs can occur if the AlGaAs layer is too thick
- Parallel conduction has detrimental consequences due to the introduction of a low-mobility parallel electron channel
- Parallel conduction can be eliminated by reducing the thickness of the AlGaAs layer, increasing the Al content in the AlGaAs layer, or by reducing the doping concentration

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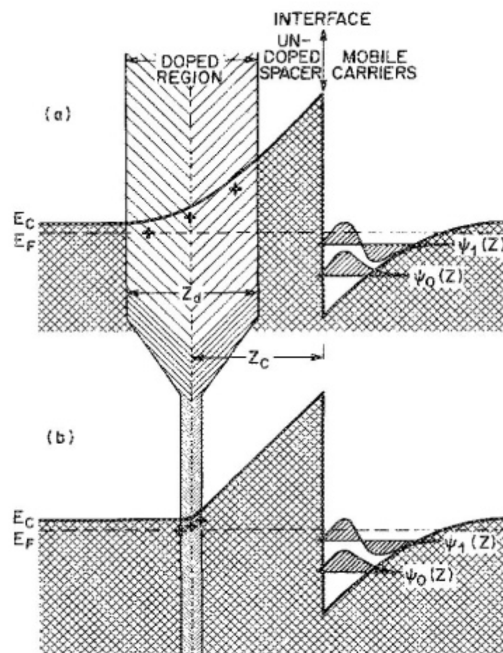
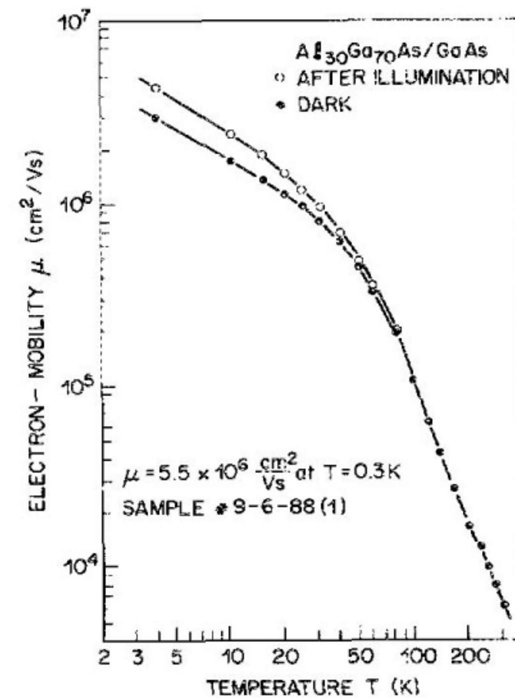
Optimum doping distribution:

Delta doping represents optimum dopant distribution in modulation-doped heterostructure:





(after AT&T Bell Laboratories Corporation, Murray Hill, NJ)

Why is delta-doped structure optimum?

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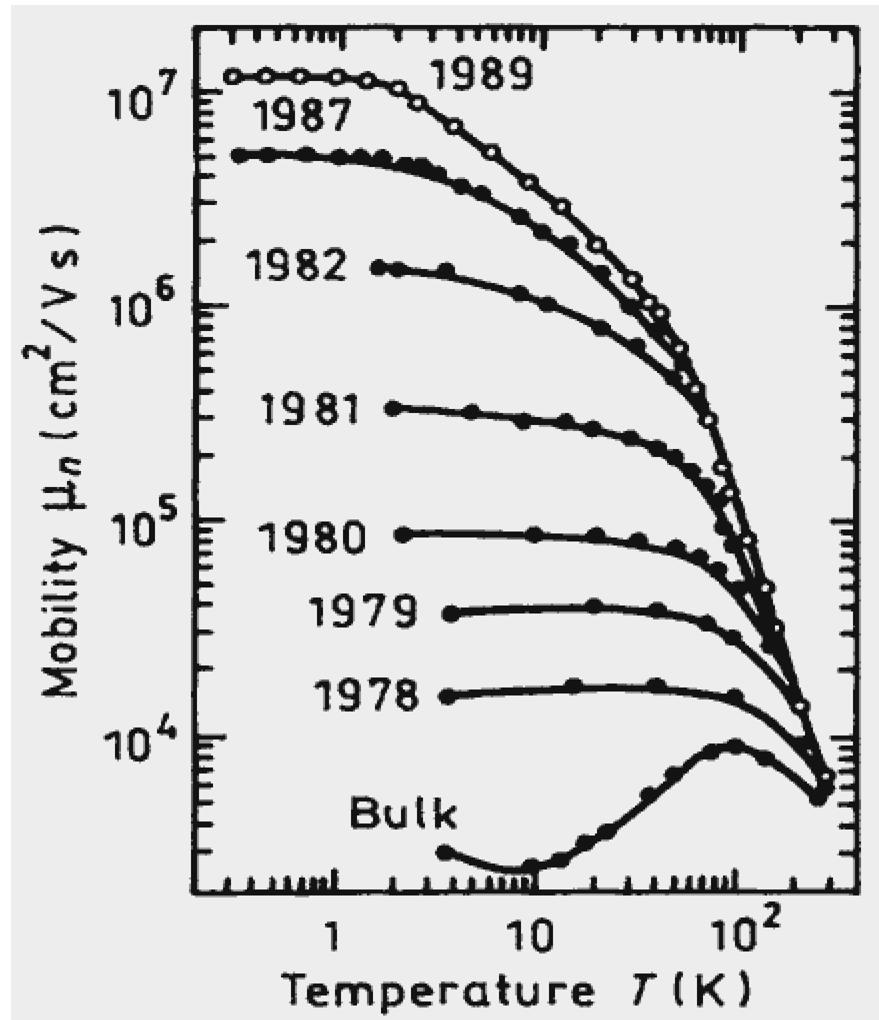
Electron mobility in AlGaAs/GaAs heterostructures versus year:



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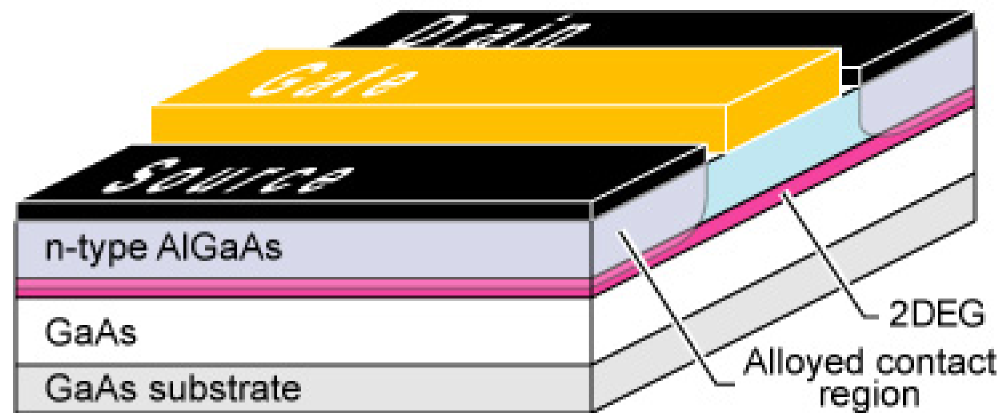
HEMTs

Modulation-doped FET or **HEMT** structure:



Geometrical advantages of HEMT over MESFET:

(1) Electron channel is well confined. Electrons are confined to the AlGaAs / GaAs interface

(2) The following is desirable: Channel width << gate-to-channel distance << gate length. This can be more easily attained with a HEMT, compared with a MESFET.

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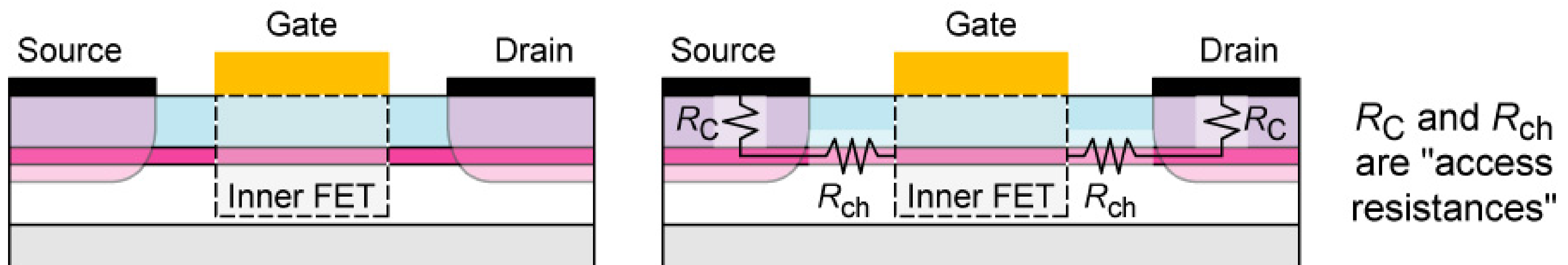
Performance advantages of HEMT over MESFET:

(1) Higher transconductance due to higher channel mobility (recall that this follows from Shockley's gradual channel approximation)

(2) Higher speed due to higher transconductance

(3) Reduction of parasitic and access resistances due to higher channel mobility



(3) Lower-noise performance due to reduction of access resistances

(4) Higher power efficiency due to reduction of parasitic resistances

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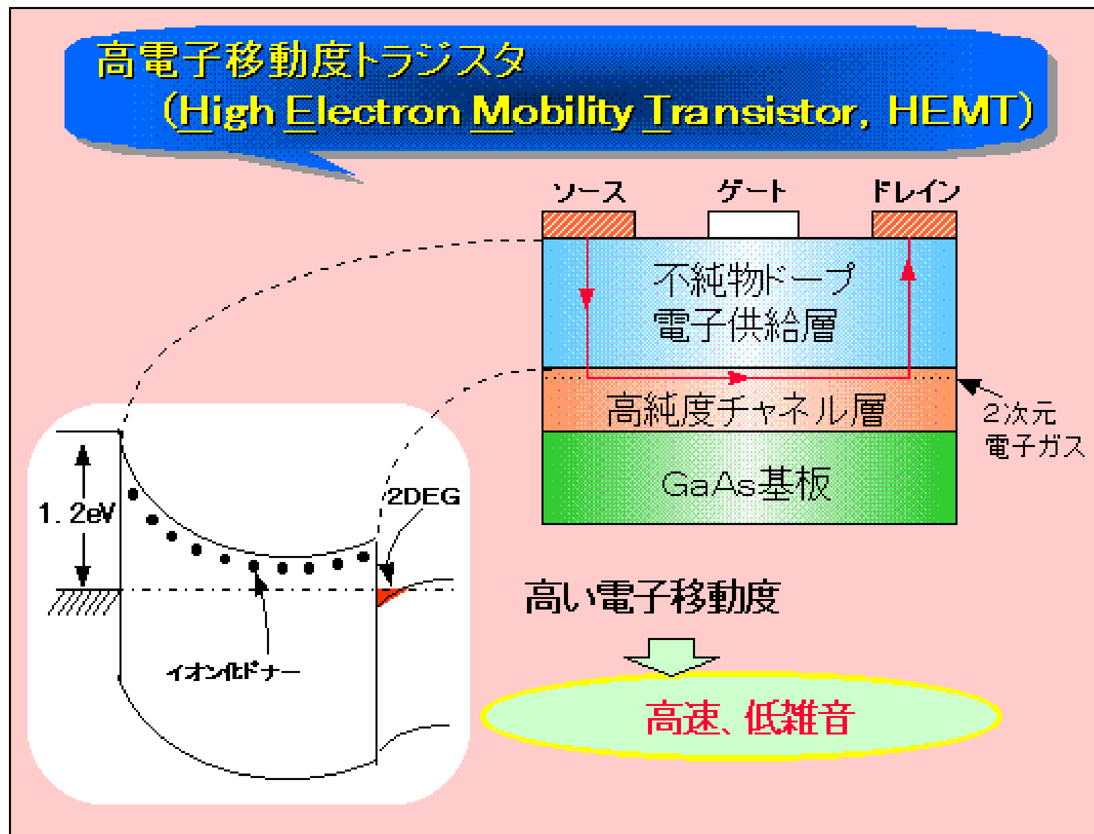
Fujitsu Corporation was the first company to commercialize HEMTs in the early 1980s



(after Fujitsu Corporation, Japan)

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Report in 2002: Fujitsu announces fastest transistor

A group at Fujitsu Laboratories in Japan has continued with its run of record breaking devices by reporting an InP-based HEMT with an f_t of 562 GHz, making it the fastest transistor ever made The group has set records in the past for its lattice-matched and pseudomorphic InP-based devices. In *IEEE Electron Device Letters* (Vol. **23**, No. 10, 2002), Akira Endo and colleagues at Fujitsu, in collaboration with researchers at Osaka University and the Communications Research Laboratory in Tokyo, described the fabrication methods used to make the 25 nm gate length device.

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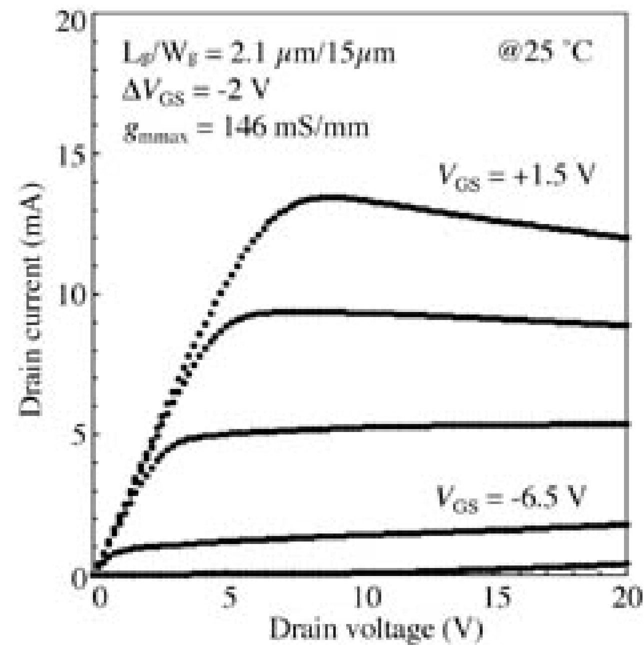
Example of HEMT I-V characteristic



(after Nagoya Institute of Technology, Japan)

The output characteristic reveals gain compression.

What is gain compression?
What is the physical origin of gain compression?

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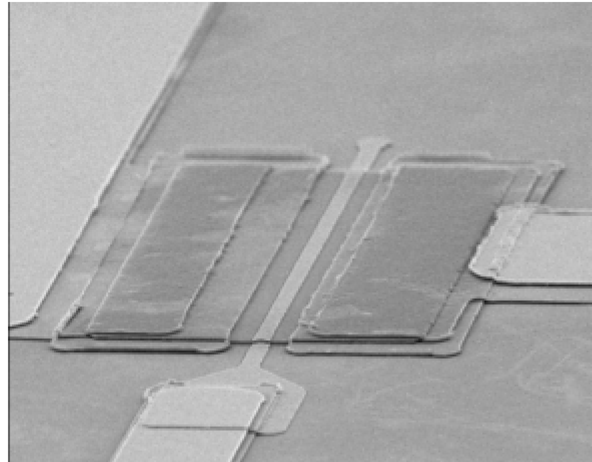
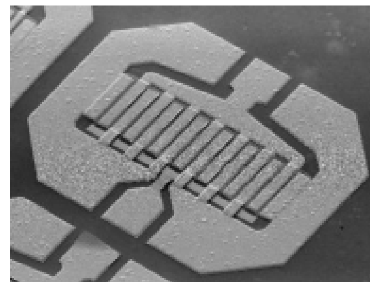
Example of photograph of HEMT



(after Research Institute on Communication Technology, Netherlands)

Example of photograph of HEMT



(after SVT Associates)

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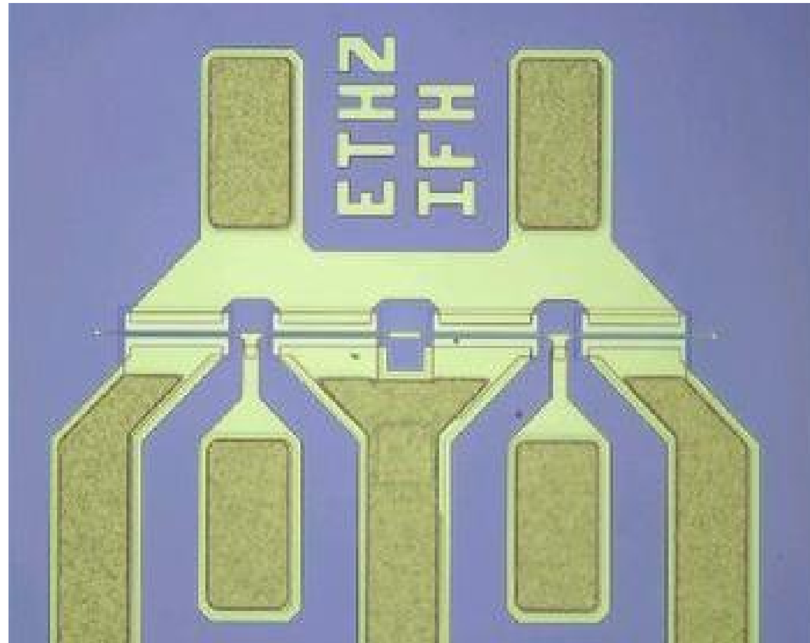
Example of HEMT with T-shaped gate



(after ETH Zurich, Switzerland)

What is advantage of T-shaped gate?

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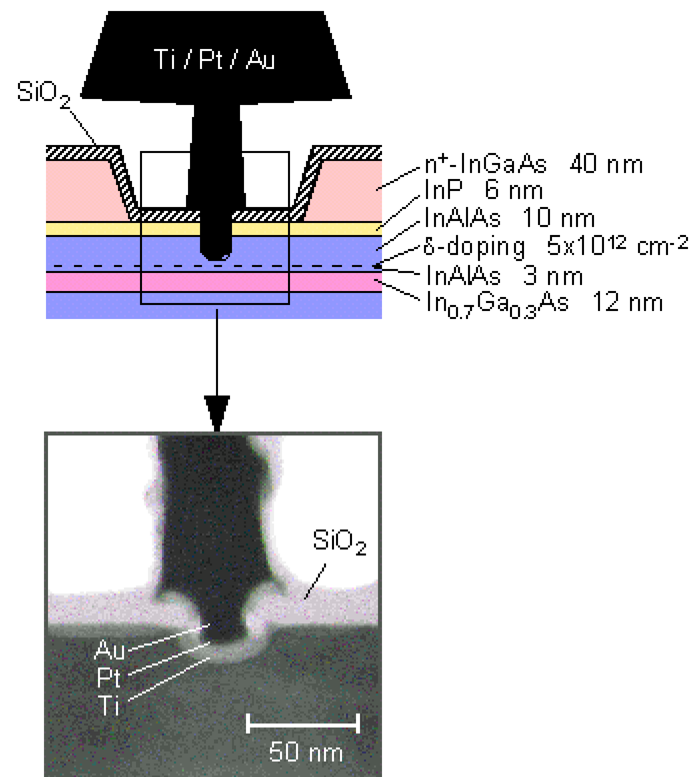
Example of advanced HEMT structure with mushroom-shaped gate structure:



(after Fujitsu Corporation, Japan)

What is advantage of mushroom-shaped gate?

Note that figure shows delta-function-like doping profile.

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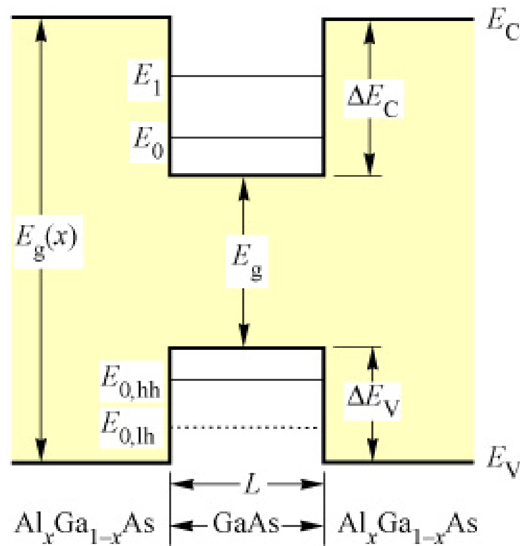
Appendix: Material parameters of AlGaAs:



$$E_{g,\ Al_xGa_{1-x}As} = (1.424 + 1.247 \times x)\ \text{eV}$$

$$\Delta E_c = (2/3)\ \Delta E_g$$

$$\Delta E_v = (1/3)\ \Delta E_g$$

$$\varepsilon_{r,\ Al_xGa_{1-x}As} = 13.1 - 3.0\ x$$

$$m^*_{e,\ Al_xGa_{1-x}As} = (0.067 + 0.083 \times x)\ m_0$$

$$m^*_{hh,\ Al_xGa_{1-x}As} = (0.45 + 0.30 \times x)\ m_0$$

$$m^*_{lh,\ Al_xGa_{1-x}As} = (0.08 + 0.057 \times x)\ m_0$$

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Appendix: Formulas of chemical compounds:

What are the internationally recognized rules for the chemical formulas of ternary and quaternary semiconductors?

Nomenclature goes from **left to right** and from **top to bottom** of periodic system of elements. Thus cations are listed before anions. Furthermore, the **stoichiometry** is expressed by the chemical formula. Thus the correct formula for aluminum gallium arsenide is $\mathbf{Al_{\mathit{x}}Ga_{1-\mathit{x}}As}$. Al is listed before Ga, because it is located higher in the periodic system. The formula also indicates that there is one cation (Al or Ga) per anion (As). $Al_xGa_{1-x}As$ is frequently abbreviated as AlGaAs. However note that AlGaAs is an abbreviation and not a correct chemical formula.

Examples of correct formulas:

Examples of abbreviations:

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