Session 5: Solid State Devices

Heterostructure Transistors

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Outline

- A
  - B
  - C
  - D
  - E
- F
  - G
- H
- I
- J

Outline

- Ref: Brennan and Brown

FETs!

Why FET is dominant:

☺ relative ease of fabrication

☺ planar geometry

☺ Reliability

☺ Reproducibility

☺ miniaturization capability

MOSFET winner:

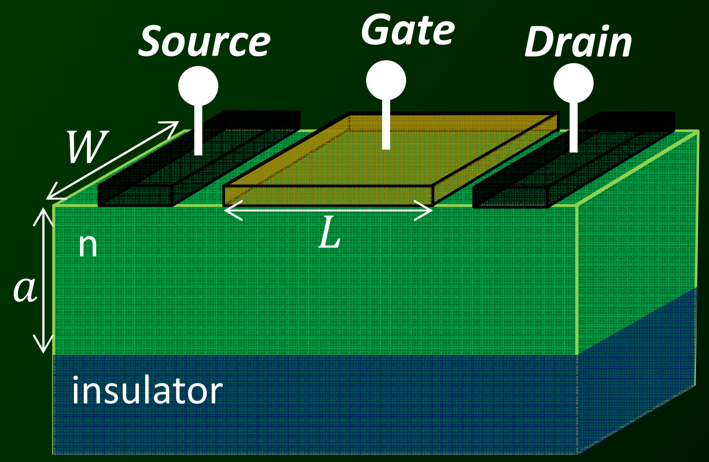
☺ easy SiO_2, good $Si–SiO_2$ interface → GSI

☹ Si inherently low-mobility material.

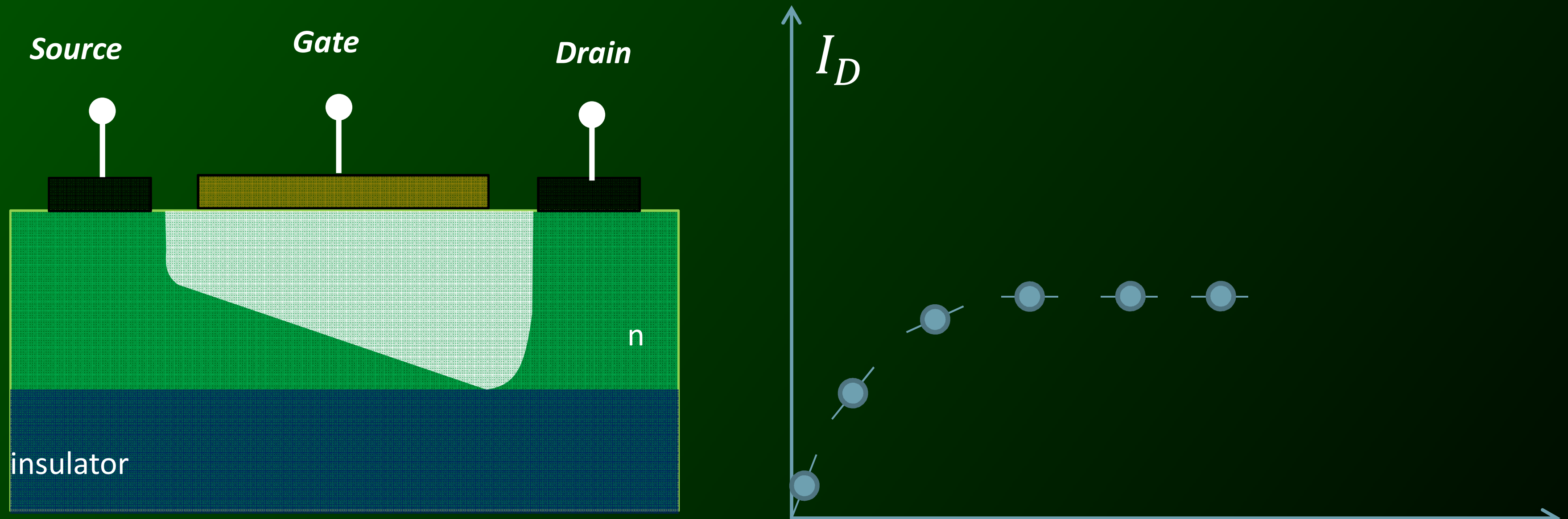
Solution: compound semiconductors

Problem: insulator

MOSFET → MESFET (Schottky barrier)



MESFET Operation



Heterostructure FET

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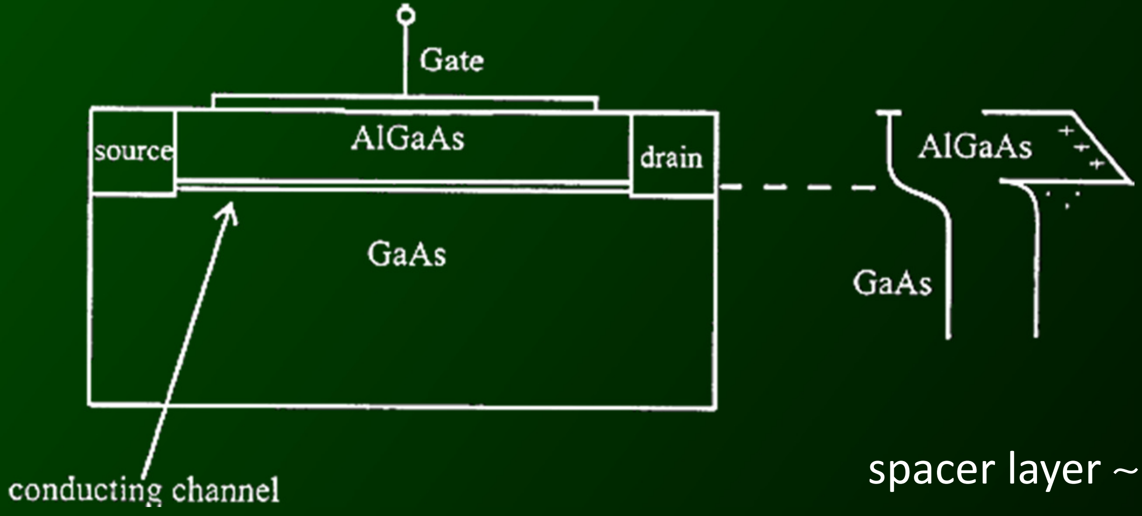
modulation-doped-field-effect transistor (MODFET)
high-electron mobility transistor (HEMT)



spacer layer ~ nm

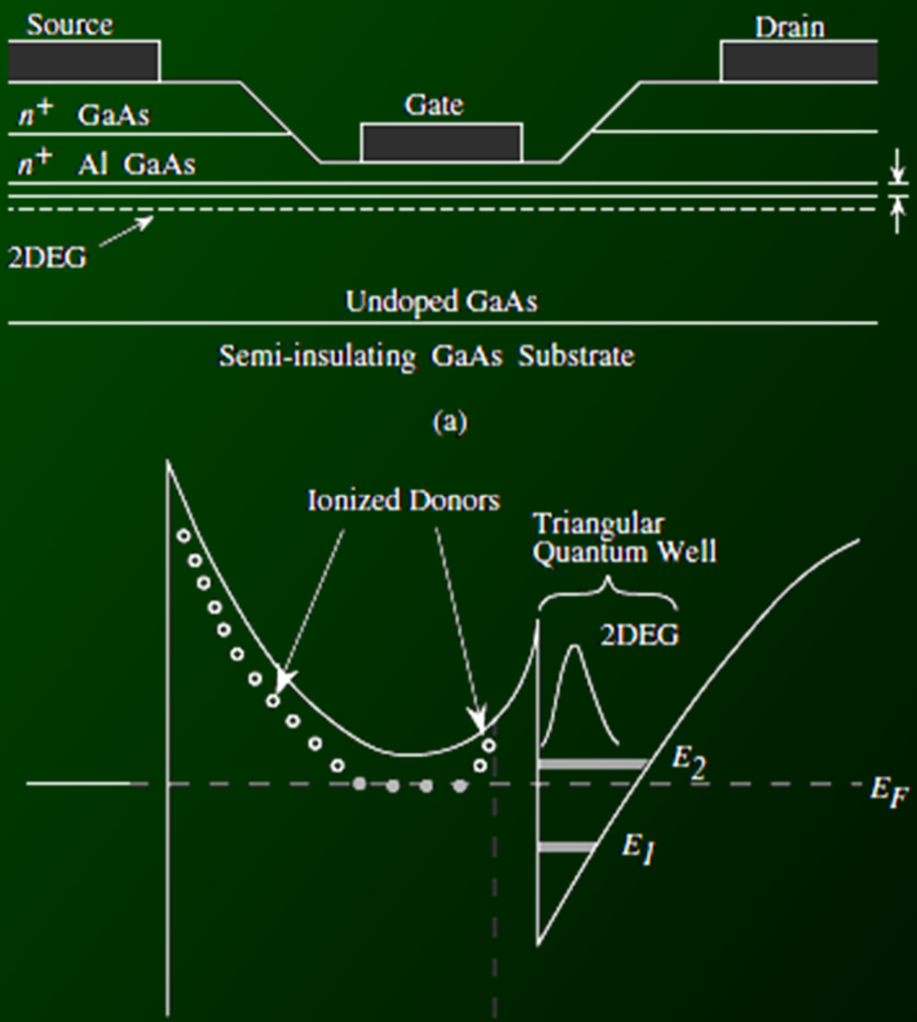
enhancement- or depletion-mode devices

transport physics of electrons in a 2D system

velocity overshoot

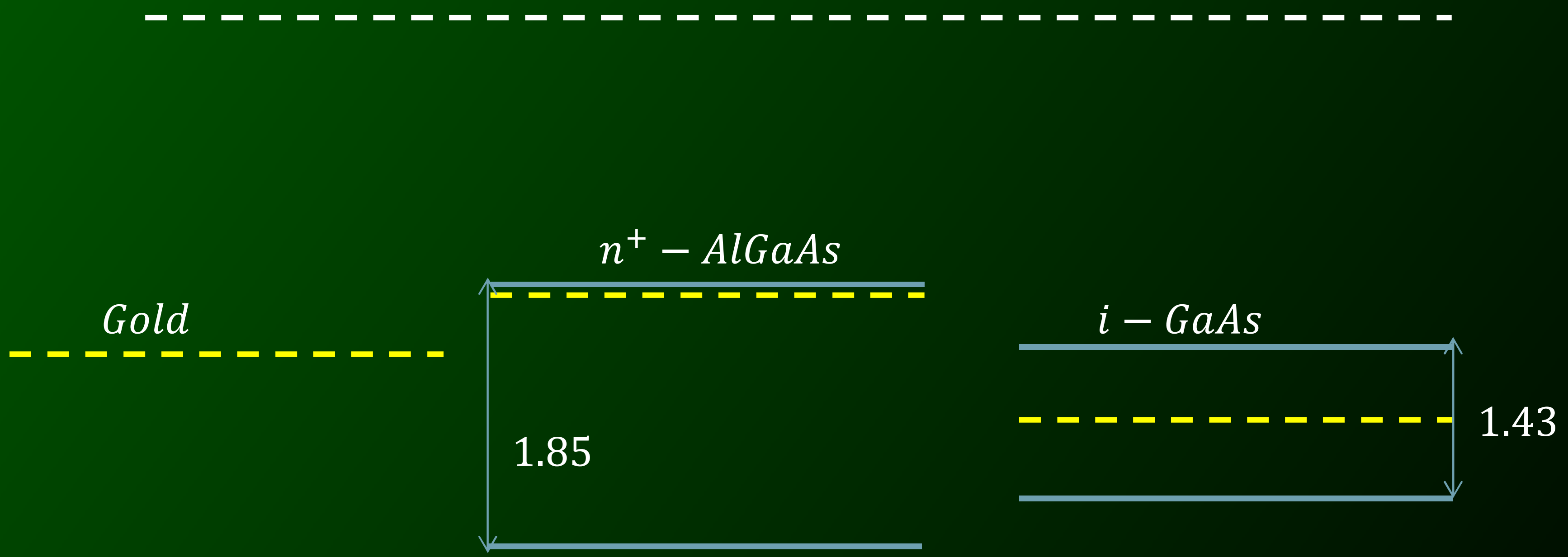
pinch-off point

Heterostructure FET

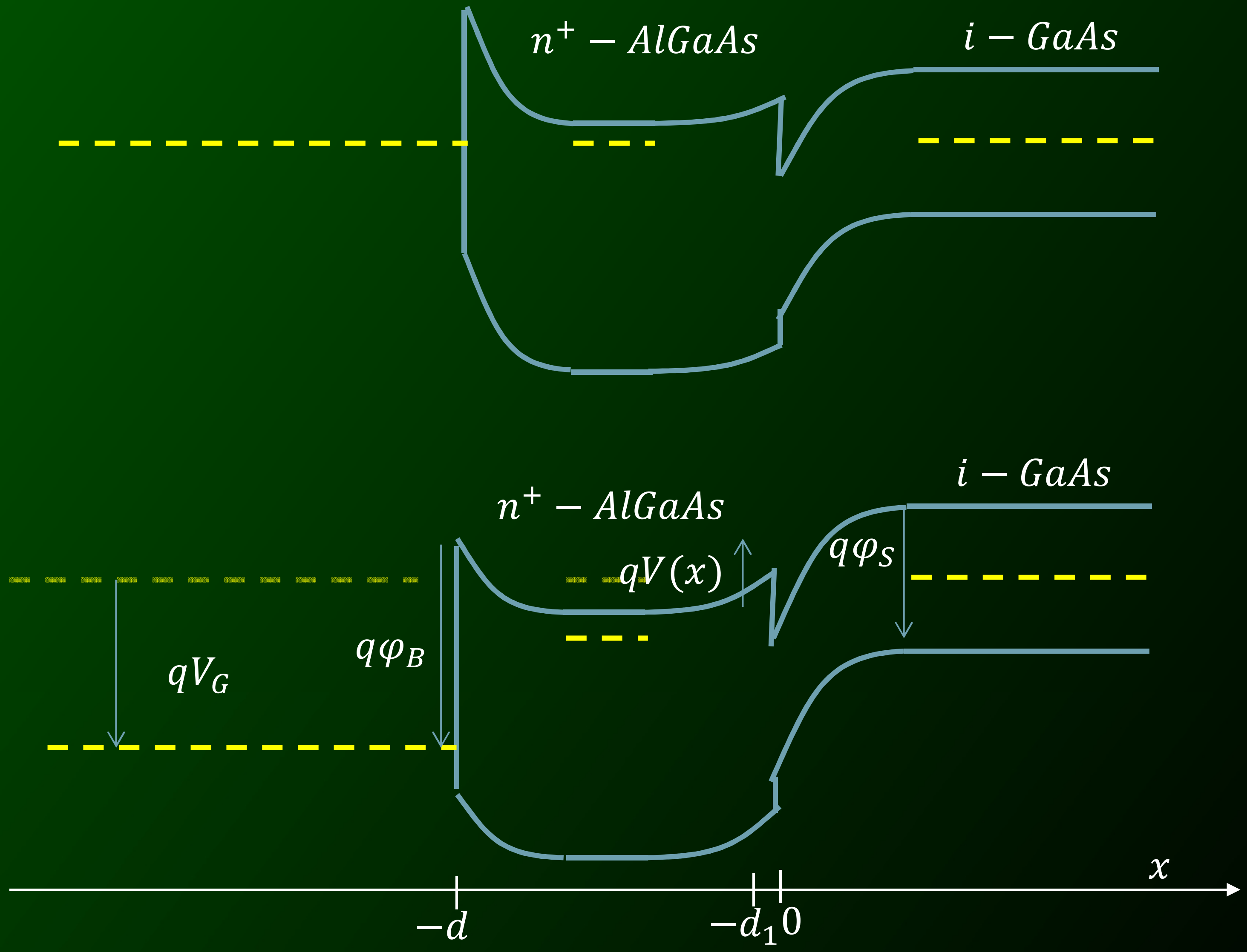


(a)

Long Channel MODFET



Long Channel MODFET



Long Channel MODFET

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$$\frac{d^2V(x)}{dx^2} = -\frac{qN_D}{\epsilon} \qquad -d < x < -d_1$$

$$\mathcal{E}(0^-) = \mathcal{E}(-d_1) = -\left.\frac{dV(x)}{dx}\right|_{x=-d_1} = \mathcal{E}_s \qquad V(-d_1) = -d_1\mathcal{E}_s$$

$$V(x) = -\mathcal{E}_s x - \frac{qN_D}{2\epsilon}(x+d_1)^2 \qquad V(-d) = \mathcal{E}_s d - \frac{qN_D}{2\epsilon}(d-d_1)^2$$

$$-V(-d) = \varphi_B - V_G - \left[\frac{\Delta E_C}{q} - \left(\varphi_S - \frac{E_F}{q}\right)\right]$$

$$-V(-d) = \varphi_B - V_G - \frac{\Delta E_C}{q} - \varphi_S + \frac{E_F}{q} = -\mathcal{E}_s d + \frac{qN_D}{2\epsilon}(d-d_1)^2$$

Long Channel MODFET

define the threshold voltage V_T below which there is no charge in the channel as

$$V_T \equiv \varphi_B - \frac{\Delta E_C}{q} - \frac{qN_D}{2\epsilon}(d - d_1)^2$$

$$\mathcal{E}_s x = V_G - V_T + \frac{E_F}{q} - \varphi_S$$

$$\epsilon \mathcal{E}_s x = \epsilon \left(V_G - V_T + \frac{E_F}{q} - \varphi_S \right) = qn(x)d$$

$$\varphi_S(x) = \frac{qn(x)d}{\epsilon} + V_G - V_T + \frac{E_F}{q}$$

$$\varphi_S(0) = \frac{qn_{S0}d}{\epsilon} + V_G - V_T + \frac{E_F}{q}$$

$$V(x) = \varphi_S(x) - \varphi_S(0) = \frac{qd}{\epsilon}(n_{S0} - n(x))$$

$$n(x) = n_{S0} - \frac{\epsilon}{qd}V(x)$$

Long Channel MODFET

$$I_C(x) = qWn(x)v(x)$$

$$v(\mathcal{E}) = \begin{cases} \dfrac{\mu|\mathcal{E}|}{1 + |\mathcal{E}|/\mathcal{E}_1}, & \mathcal{E} \le \mathcal{E}_C \\ v_{sat}, & \mathcal{E} > \mathcal{E}_C \end{cases}$$

$$I_C(x) = qWn(x)\frac{\mu(dV/dx)}{1 + (dV/dx)/\mathcal{E}_1}$$

considering gate leakage current

$$I_S = W\int_0^x j_G(x)dx + I_C(x)$$

$$I_S - W\langle j_G\rangle x = \frac{qWn(x)\mu(dV/dx)}{1 + (dV/dx)/\mathcal{E}_1}$$

$$(I_S - W\langle j_G\rangle x)(1 + (dV/dx)/\mathcal{E}_1) \;=\; qWn(x)\mu(dV/dx)$$

$$\int_0^L (I_S - W\langle j_G\rangle x)\left(1 + \frac{1}{\mathcal{E}_1}\frac{dV}{dx}\right)dx \;=\; qW\mu\int_0^{V_D} n(V)dV$$

Long Channel MODFET

$$\int_0^L (I_S - W\langle j_G\rangle x)\left(1+\frac{1}{\mathcal{E}_1}\frac{dV}{dx}\right)dx = qW\mu\int_0^{V_D} n(V)dV$$

$$L\left[I_S - \frac{1}{2}W\langle \underbrace{j_G}_{I_G}\rangle L + \frac{V_D I_S}{L\mathcal{E}_1}\right] - \frac{W\langle j_G\rangle}{\mathcal{E}_1}\int_0^L \left(x\frac{dV}{dx}\right)dx = LHS$$

$$qW\mu\int_0^{V_D} n(V)dV = qW\mu\int_0^{V_D}\left(n_{S0} - \frac{\epsilon}{qd}V(x)\right)dV = qW\mu\left(n_{S0}V_D - \frac{\epsilon V_D^2}{2qd}\right) = RHS$$

$$\frac{W\langle j_G\rangle}{\mathcal{E}_1}\int_0^L \left(x\frac{dV}{dx}\right)dx = \frac{I_G}{\mathcal{E}_1}\left[V_D - \frac{1}{L}\int_0^L V(x)dx\right] \sim \frac{I_G V_D}{2\mathcal{E}_1}$$

$$I_S = I_G + I_D$$

Long Channel MODFET

$$L\left[I_D - \tfrac{1}{2}I_G + \frac{V_D}{L\mathcal{E}_1}(I_D + I_G)\right] - \frac{I_G V_D}{2\mathcal{E}_1} = qW\mu(n_{S0}V_D - \frac{\epsilon V_D^2}{2qd})$$

$$I_D = \frac{1}{1 + \frac{V_D}{L\mathcal{E}_1}}\left\{\left[-\tfrac{1}{2}I_G\left(1 + \frac{V_D}{L\mathcal{E}_1}\right)\right] + \frac{qW\mu}{L}(n_{S0}V_D - \frac{\epsilon V_D^2}{2qd})\right\}$$

drain current in the linear region of a MODFET

At saturation: $I_C(x) = qWn(x)v_{sat}$

$$I_{Dsat} = qW\left(n_{S0} - \frac{\epsilon V(L)}{qd}\right)v_{sat} = qW(n_{S0} - \frac{\epsilon V_{Dsat}}{qd})v_{sat}$$

$$I_G = I_{S1}\left(e^{qV_G/\eta_1 kT} - 1\right)$$

$$I_G = I_{S2}e^{qV_G/\eta_2 kT}$$

$$\frac{V_D}{L\mathcal{E}_1} \ll 1$$

$$I_G \sim 0$$

$$I_D = \frac{qW\mu}{L}(n_{S0}V_D - \frac{\epsilon V_D^2}{2qd})$$

Ex.3.3.1

Find V_T of a GaAs–AlGaAs MODFET:

Al composition is 25%. Assume a conduction band to valence band discontinuity ratio of 60%/40%, that the Schottky barrier height is 1.0 V, and that the AlGaAs layer is 33.0 nm thick with an undoped spacer layer of 3.0 nm

$$Al_xGa_{1-x}As\text{:}\ \ E_G = 1.424 - 1.247x = 1.736\ eV$$

$$\Delta E_C = 0.6 \times (1.736 - 1.424) = 0.187\ eV$$

$$V_T = 1.0 - \frac{0.187}{q} - \frac{(1.6 \times 10^{-19})(10^{18})((33-3)\times 10^{-7})}{2 \times 12.4 \times 8.85 \times 10^{-14}}$$

$$= 0.157$$

MODFET vs. MOSFET

$$I_D = \frac{qW\mu}{L}\left(n_{S0}V_D - \frac{\epsilon V_D^2}{2qd}\right)$$

$$I_D = \frac{W\mu}{L}\left(qn_{S0}V_D - \frac{\epsilon V_D^2}{2d}\right) = \frac{W\mu}{L}\left(Q_n V_D - \frac{\epsilon V_D^2}{2d}\right)$$

$$Q_n = C_{ox}(V_G - V_T) \qquad C_{ox} = \frac{\epsilon}{d}$$

$$I_D = \frac{W\mu}{L}\left(Q_n V_D - \frac{\epsilon V_D^2}{2d}\right)$$

$$I_D = \frac{W\mu C_{ox}}{L}\left((V_G - V_T)V_D - \frac{V_D^2}{2}\right)$$

Advanced MODFETs

$$\frac{dP}{dt} = -qn\mathcal{E} - \frac{P}{\tau_m}$$

τ_m momentum relaxation time

$$\bar{P} = q\mathcal{E}\tau_m\left(e^{-t/\tau_m} - 1\right)$$

$$\bar{v} = \frac{q\mathcal{E}\tau_m}{m^*}\left(e^{-t/\tau_m} - 1\right)$$

$$d = \frac{1}{m^*}\int_0^{\tau_m} q\mathcal{E}\tau_m\left(e^{-t/\tau_m} - 1\right)dt = \frac{q\mathcal{E}\tau_m^2}{e\,m^*}$$

$\mathcal{E} = 10kV/cm$

$d_{Si} = 11nm$

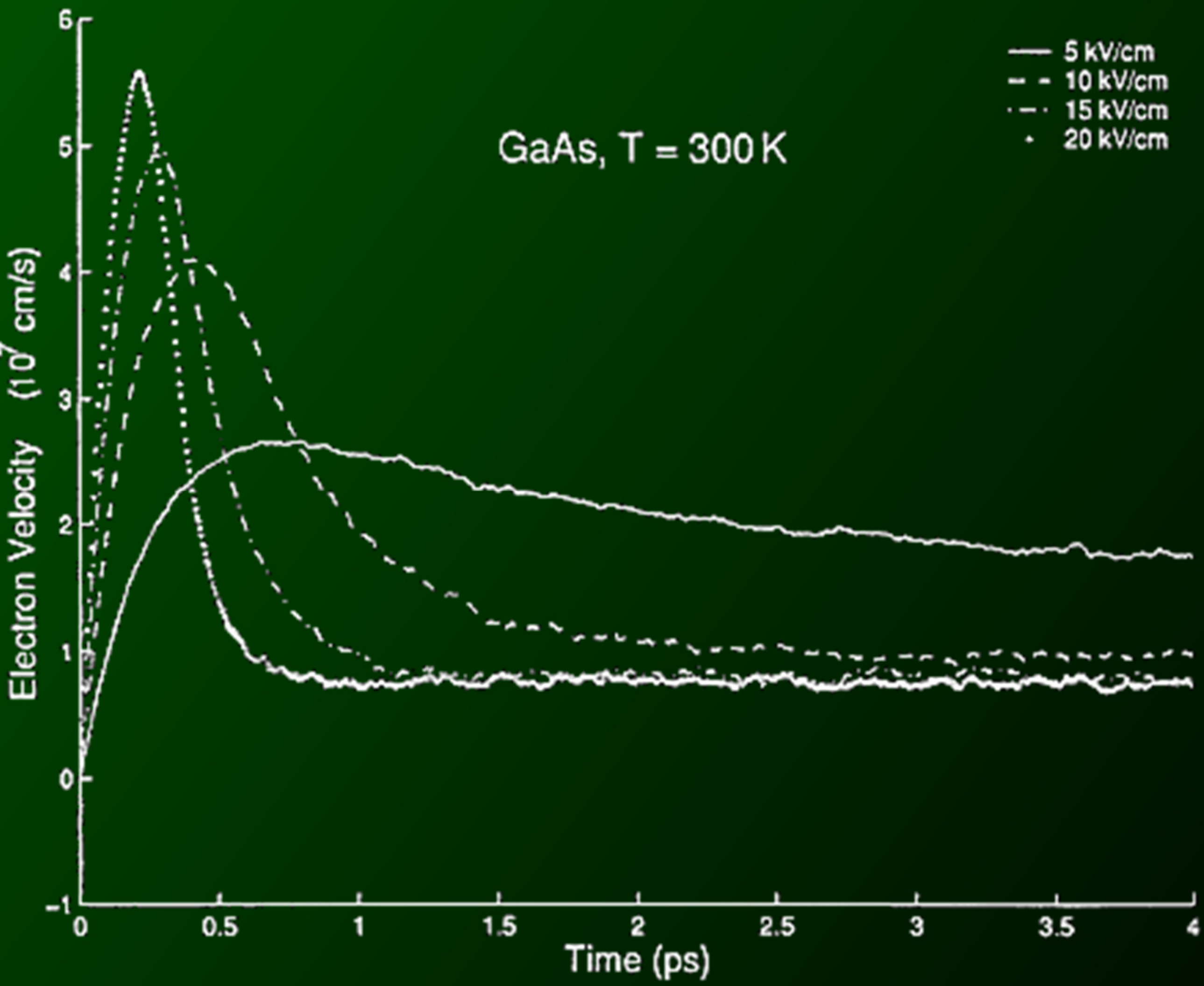
$d_{GaAs} = 100nm$

velocity overshoot

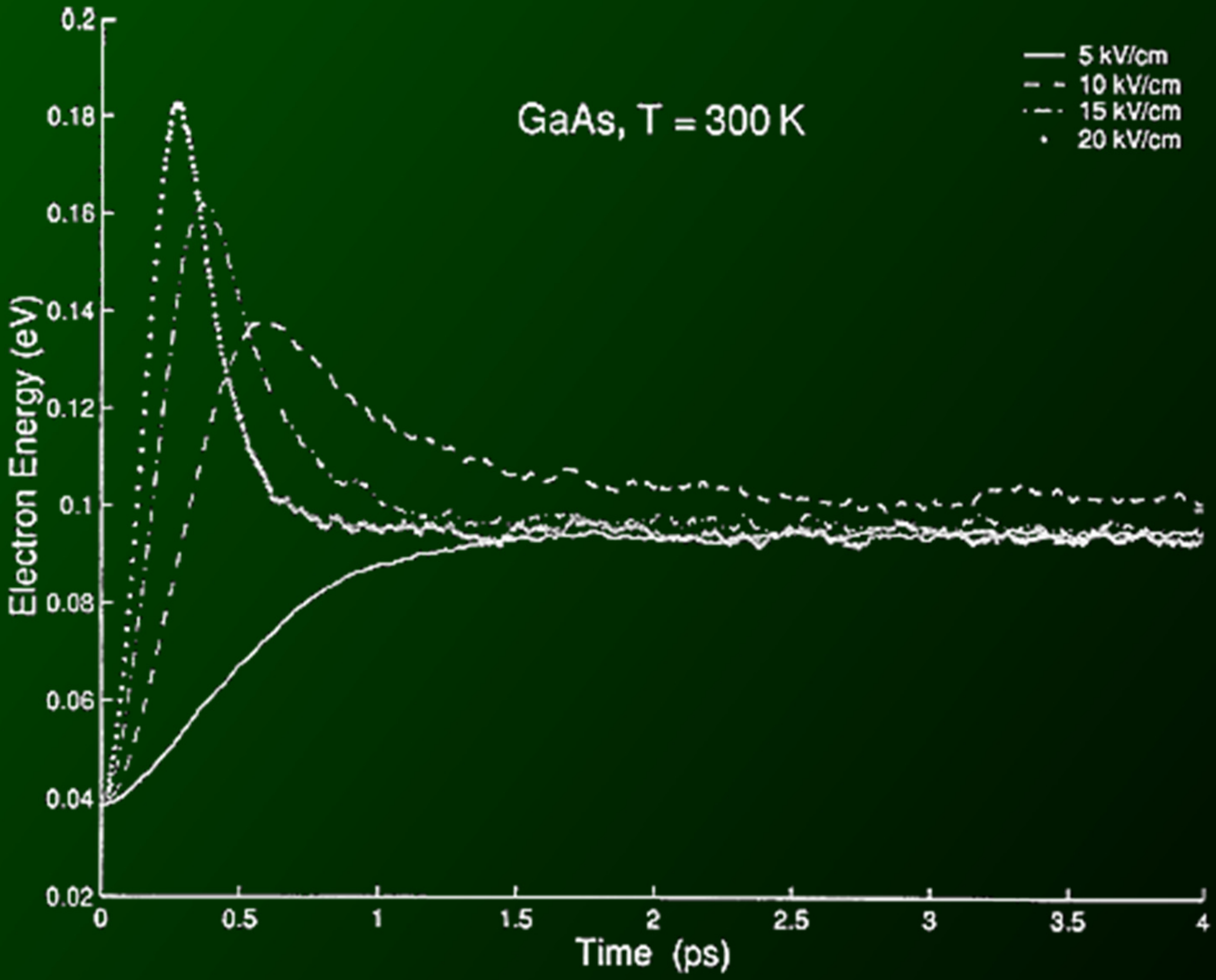
$$\frac{d\bar{E}}{dt} = -q\bar{v}\mathcal{E} - \frac{\bar{E} - \overline{E_0}}{\tau_E}$$

$$\bar{E} = (q\bar{v}\mathcal{E}\tau_E - \overline{E_0})\left(e^{-t/\tau_m} - 1\right)$$

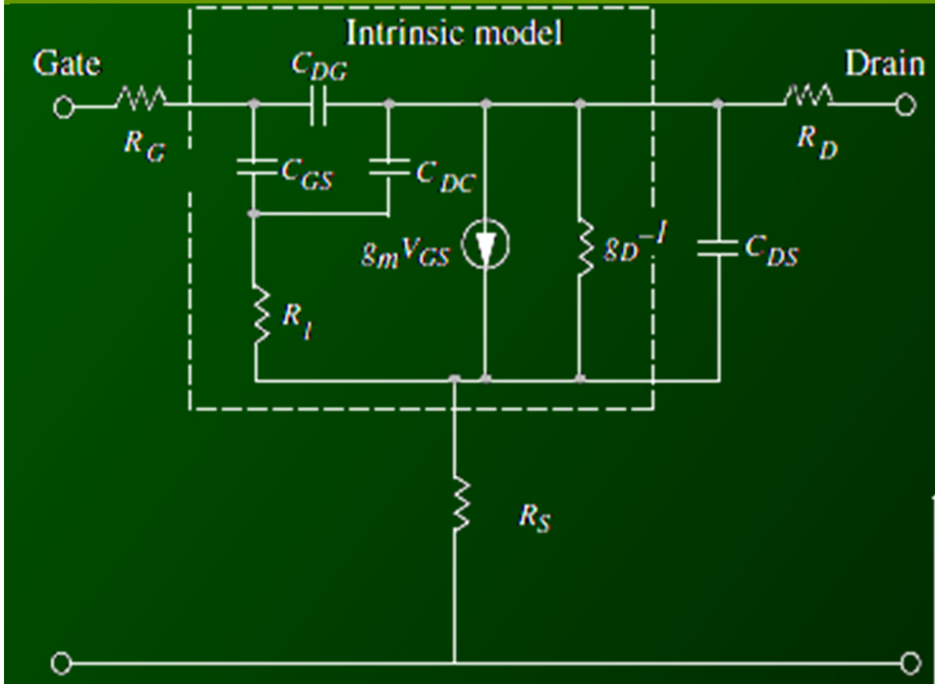
Velocity Overshoot



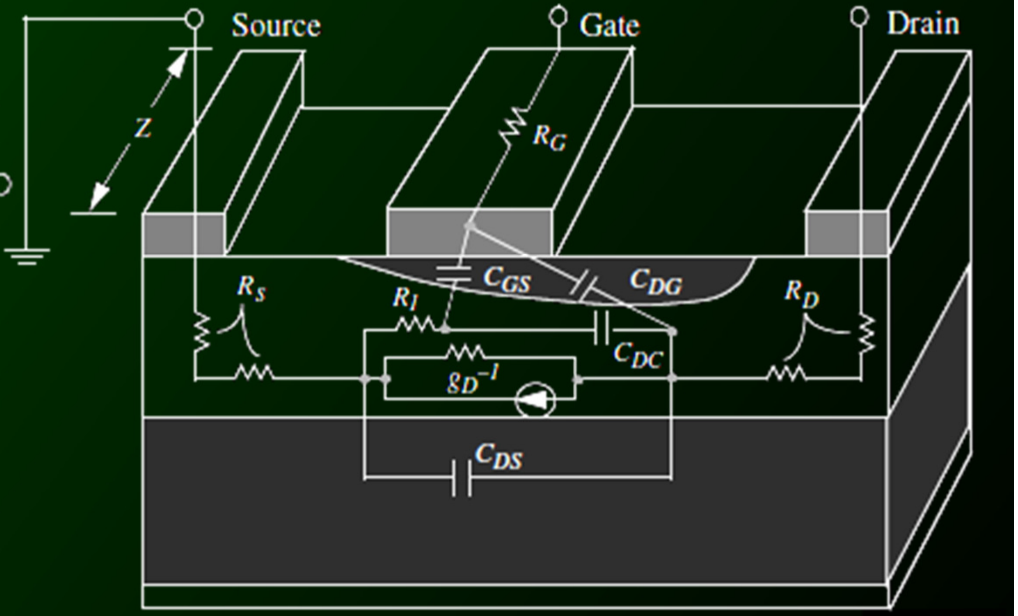
Energy Overshoot



Small Signal Model



$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} = \frac{C_G}{t_{tr}}$$



$$f_T = \frac{g_m}{2\pi C_G} = \frac{v}{2\pi L}$$

Material Select

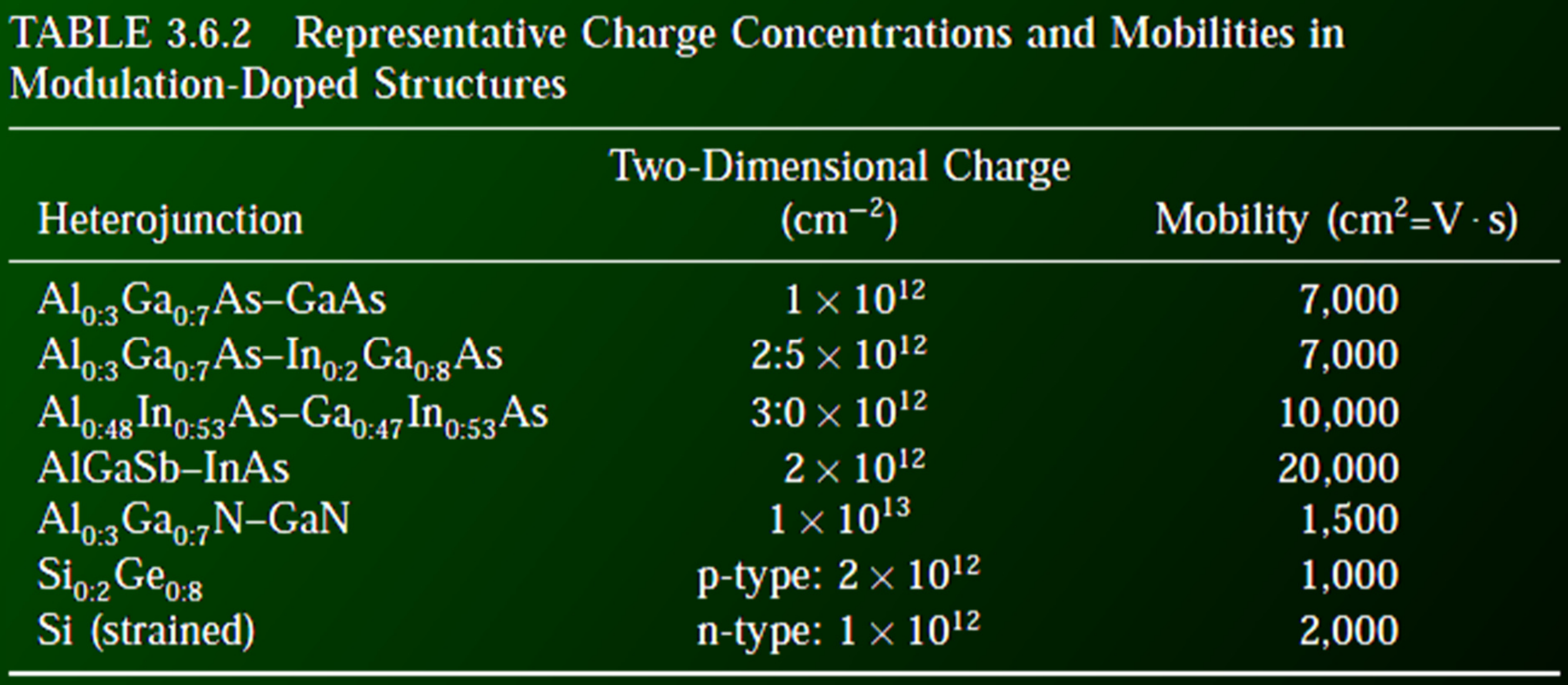


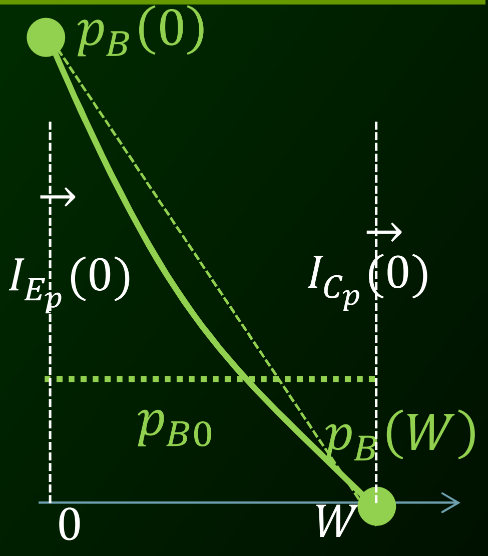
TABLE 3.6.2 Representative Charge Concentrations and Mobilities in Modulation-Doped Structures

Heterojunction	Two-Dimensional Charge (cm^{-2})	Mobility (cm^2=V · s)
$Al_{0:3}Ga_{0:7}As$–GaAs	1×10^{12}	7,000
$Al_{0:3}Ga_{0:7}As$–$In_{0:2}Ga_{0:8}As$	$2:5 \times 10^{12}$	7,000
$Al_{0:48}In_{0:53}As$–$Ga_{0:47}In_{0:53}As$	$3:0 \times 10^{12}$	10,000
AlGaSb–InAs	2×10^{12}	20,000
$Al_{0:3}Ga_{0:7}N$–GaN	1×10^{13}	1,500
$Si_{0:2}Ge_{0:8}$	p-type: 2×10^{12}	1,000
Si (strained)	n-type: 1×10^{12}	2,000

BJT - Considering Recombination in Base

$$\Delta p_B(x) = B_1 e^{x/L_B} + B_2 e^{-x/L_B}$$

$$\begin{cases} \Delta p_B(W) = p_{B0}(e^{qV_{CB}/kT} - 1) \\ \Delta p_B(0) = p_{B0}(e^{qV_{EB}/kT} - 1) \end{cases}$$



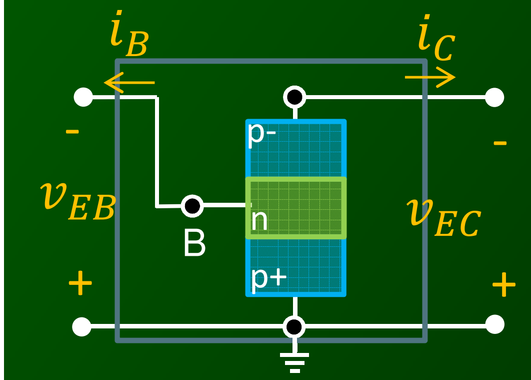
$$\Delta p_B(x) = p_{B0}(e^{\frac{qV_{EB}}{kT}} - 1)\frac{\sinh\frac{W-x}{L_B}}{\sinh\frac{W}{L_B}} + p_{B0}(e^{\frac{qV_{CB}}{kT}} - 1)\frac{\sinh\frac{x}{L_B}}{\sinh\frac{W}{L_B}}$$

$$I_E = qA\left[\frac{D_E n_{E0}}{L_E} + \frac{D_B p_{B0}}{L_B}\coth\frac{W}{L_B}\right]\left(e^{\frac{qV_{EB}}{kT}} - 1\right) - qA\frac{D_B p_{B0}}{L_B}\,(e^{\frac{qV_{CB}}{kT}} - 1)\frac{1}{\sinh\frac{W}{L_B}}$$

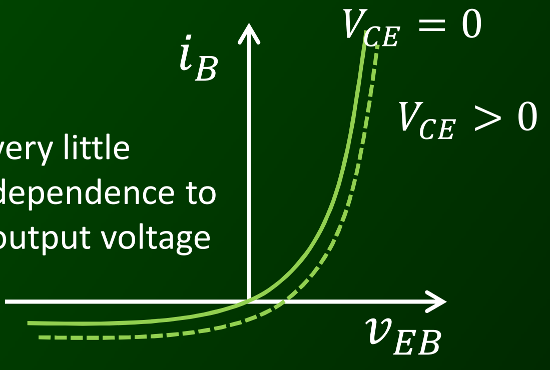
$$I_C = qA\frac{D_B p_{B0}}{L_B}\,(e^{\frac{qV_{EB}}{kT}} - 1)\frac{1}{\sinh\frac{W}{L_B}} - qA\left[\frac{D_B p_{B0}}{L_B}\coth\frac{W}{L_B} + \frac{D_C n_{C0}}{L_C}\right](e^{\frac{qV_{CB}}{kT}} - 1)$$

$$I_B = I_E - I_C$$

BJT to HBT (Common Emitter)

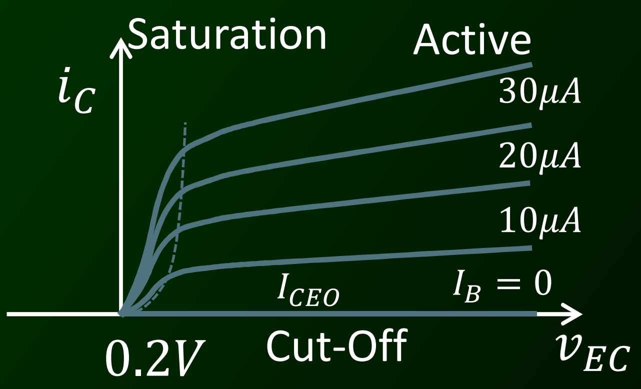


Input Characteristic



very little dependence to output voltage

Output Characteristic



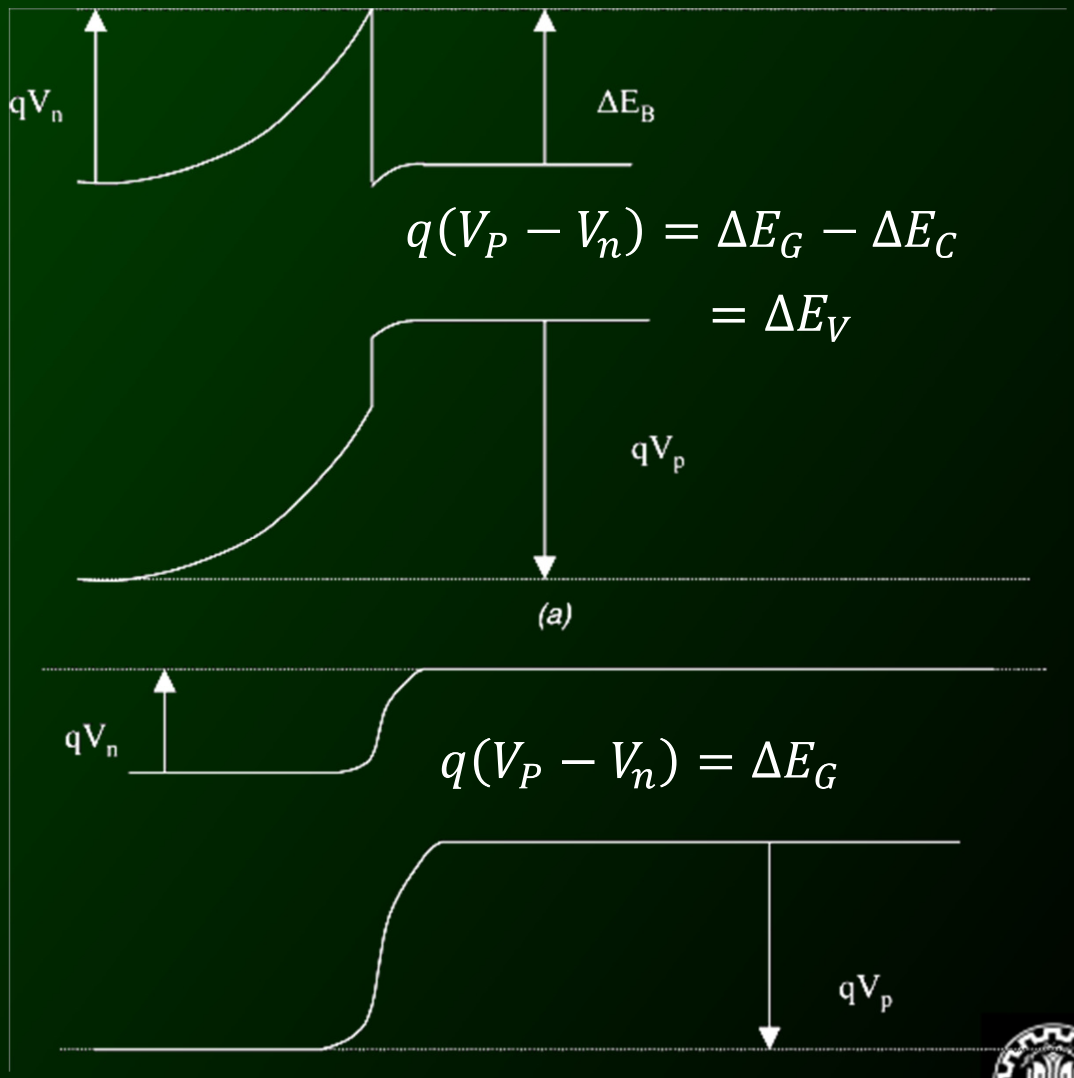
$$\left.\begin{array}{r} W \ll L\_C \\ V_{CB}<0 \\ V_{EB}>0 \end{array}\right\} \rightarrow \left\{\begin{array}{l} I_C \approx qA\dfrac{D_B p_{B0}}{W} e^{\frac{qV_{EB}}{kT}} \\ I_B \approx qA\dfrac{D_E n_{E0}}{L_E} e^{\frac{qV_{EB}}{kT}} \end{array}\right. \rightarrow \beta_{dc}=\frac{I_C}{I_B}=\frac{D_B}{D_E}\cdot\underset{\frac{N_{AE}}{N_{DB}}\upuparrows}{\frac{p_{B0}}{n_{E0}}}\cdot\frac{L_E}{W}\downdownarrows$$

$$\rightarrow \beta_{dc}=\frac{I_C}{I_B}=\frac{D_B}{D_E}\cdot\frac{p_{B0}}{n_{E0}}\cdot\frac{L_E}{W}=\frac{D_B}{D_E}\cdot\frac{N_E}{N_B}\cdot\frac{L_E}{W}\cdot\frac{n_{iB}^2}{n_{IE}^2}$$

For Al0:3Ga0:7As emitter and a GaAs base, $\frac{n_{iB}^2}{n_{IE}^2}\sim 10^5$

HBT

HBT devices can be made using either an abrupt or graded heterojunction to form the emitter–base junction.



$$q(V_P - V_n) = \Delta E_G - \Delta E_C$$
$$= \Delta E_V$$

$$J_N = N_{DE} v_n e^{-V_n/\varphi_T}$$

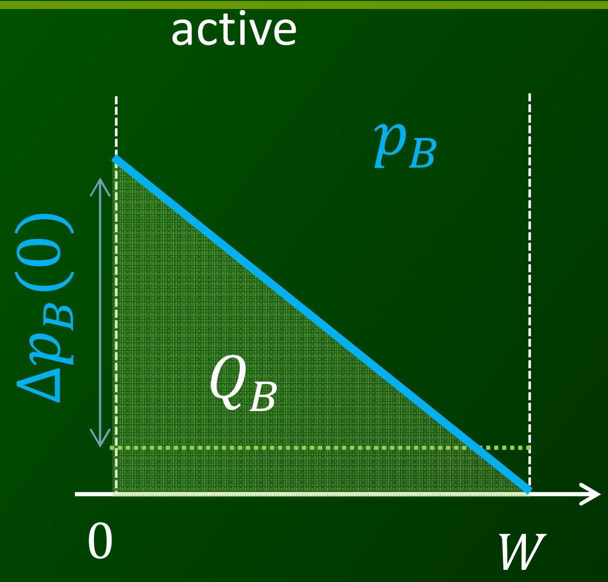
$$J_P = N_{AB} v_p e^{-V_p/\varphi_T}$$

$$q(V_P - V_n) = \Delta E_G$$

$$\beta_{DC} = \frac{J_N}{J_P}$$

Ex. 4.2.1 $\dfrac{\beta_{DC_{graded}}}{\beta_{DC_{abrupt}}} = 103$

Base Transient Time



$$Q_B = qA\frac{W\Delta p_B(0)}{2}$$

$$I_C = -qAD_B \left.\frac{\partial \Delta p_B}{\partial x}\right|_{x=W}$$

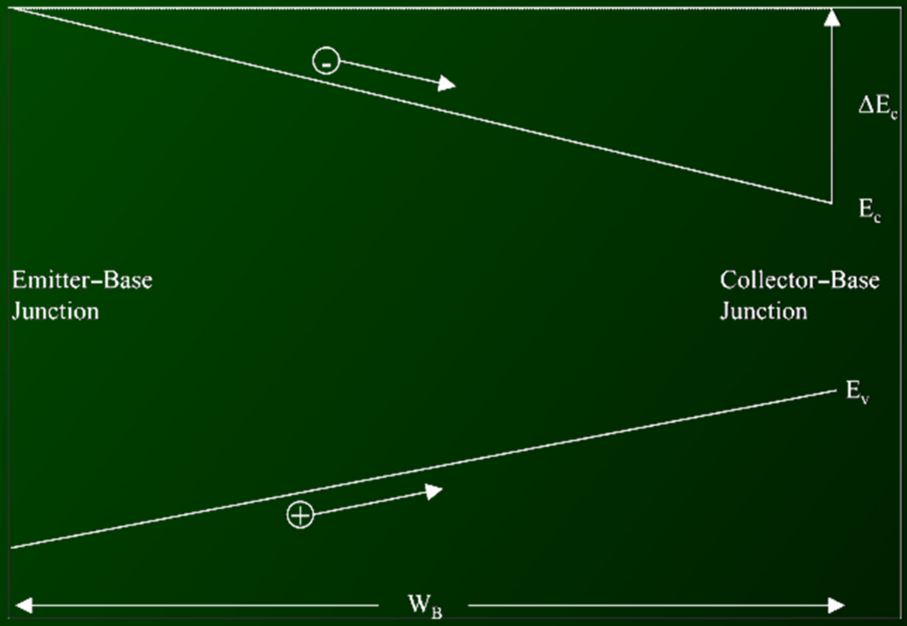
$$= qAD_B\frac{\Delta p_B(0,t)}{W}$$

$$= qAD_B\frac{2Q_B}{qAW^2}$$

$$I_C = \frac{Q_B}{(W^2/2D_B)} = \frac{Q_B}{\tau_t}$$

$$\boxed{\tau_t = \frac{W^2}{2D_B}}$$

Base Transit Time



$$\tau'_t = \frac{qW^2}{2\mu_B \Delta E_C}$$

$$\frac{\tau'_t}{\tau_t} = \frac{2kT}{\Delta E_C}$$

$$\tau_t = \frac{W^2}{2D_B}$$

HBT

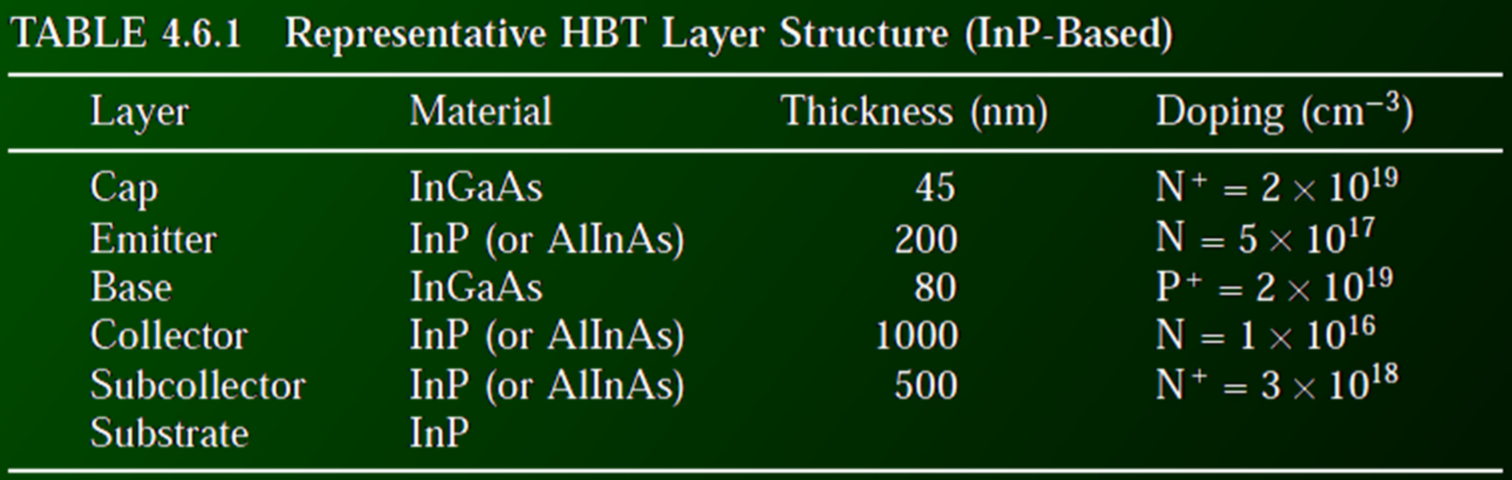
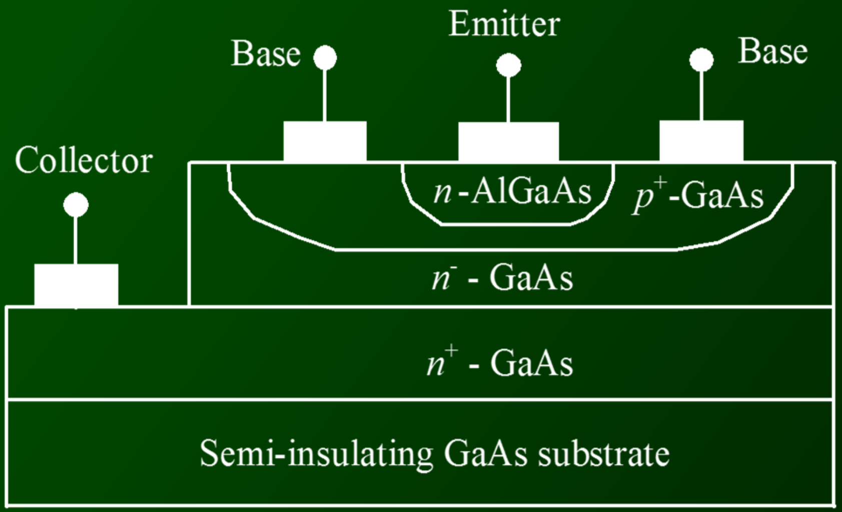


TABLE 4.6.1 Representative HBT Layer Structure (InP-Based)

Layer	Material	Thickness (nm)	Doping (cm^{-3})
Cap	InGaAs	45	$N^+ = 2 \times 10^{19}$
Emitter	InP (or AlInAs)	200	$N = 5 \times 10^{17}$
Base	InGaAs	80	$P^+ = 2 \times 10^{19}$
Collector	InP (or AlInAs)	1000	$N = 1 \times 10^{16}$
Subcollector	InP (or AlInAs)	500	$N^+ = 3 \times 10^{18}$
Substrate	InP		

HBT

AlGaAs HBT for integrated circuit made by planar process



- forward-bias emitter injection efficiency is very high since wider bandgap AlGaAs emitter injects electrons into GaAs p-base at lower energy level, but holes are prevented from flowing into emitter by high energy barrier, thus resulting in possibility to decrease base length, base-width modulation and increase frequency response

- heavily p-doped base to reduce base resistance

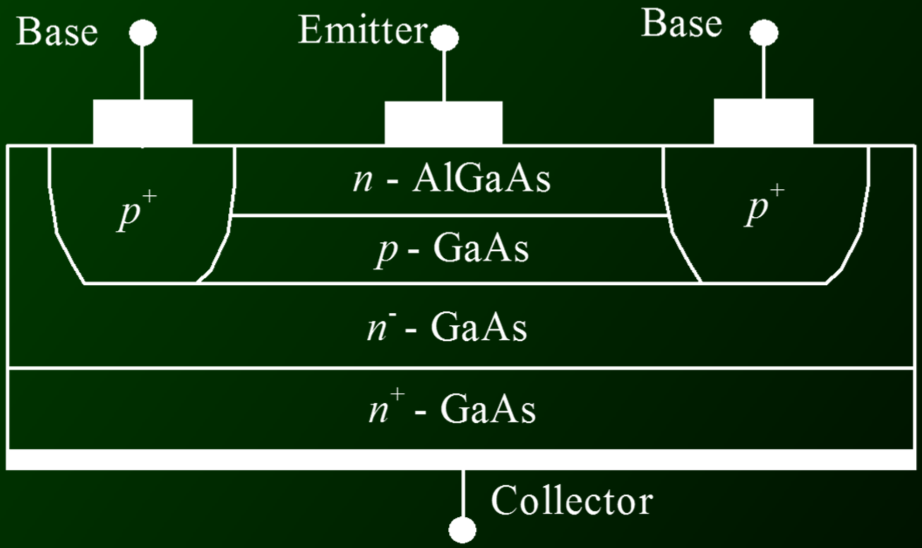
- lightly n-doped emitter to minimize emitter capacitance

- lightly n-doped collector region allows collector-base junction to sustain relatively high voltages without breaking down

HBT

Simplified structures of n-p-n heterojunction bipolar transistor (HBT)

Single-chip AlGaAs/GaAs HBT



- lower 1/f noise since surface states of GaAs no longer contribute significant noise to emitter current

- using wide bandgap InGaP layer instead of AlGaAs results in improvement of device performance over temperature

HBT

HBT

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HBT

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